Workshop on the science of Fusion ignition on NIF:

Ablation Physics

Compiled by Jim Hammer from contributions by many LLNL scientists
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Lawrence Livermore National Laboratory

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Almost every stage of the present ignition implosion exposes challenges to our current understanding

Laser Energy = 1.6 MJ

Laser propagation and x-ray conversion physics

X-ray Energy = 1.1 MJ

Ablator not "seeing" applied/ measured drive?

X-ray transport and ablation physics

Energy to capsule ~ 150 kJ
Sets DT fuel adiabat

Ablator trajectory is late?

Implosion hydrodynamics

Fuel K.E. = 12 KJ, Shell K.E. ~ 20 KJ

Implosion velocity is low, shell is thick?

Stagnation Physics

Hot spot ~ 3KJ

Role of Mix?

Yields, rho-R, <u>pressures</u> are low? Hot-spot T_{ion} is too high (except past mix cliff)? Asymmetry in rho-R?

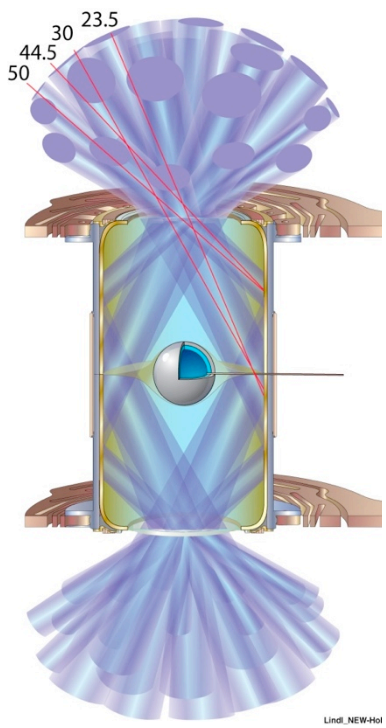
Ignition physics

Ignition & burn propagation

Not here yet…

Each stage compounds uncertainties – suggests trying to separate physics, starting with "1D hydro", the x-ray drive and ablator response

Design codes and experiments, both integrated and ”targeted,” can be used to explore why the NIC capsules differ from nominal models



- There are 2 possibilities for a slower, thicker shell:
  1) the x-ray drive is different than modeled
  2) the ablator response to the drive is different than modeled
- Low observed stagnation pressures may be due”1D” physics, e.g., an extra shock that raises DT entropy – possibly due to anomalous ablator response
- X-ray drive on the capsule could be influenced by distribution of high-Z matter within the hohlraum, e.g. by gas/wall mix, changing capsule view-factors, or LEH closure changing Dante interpretation
- Equation of state (EOS) and opacity may be different than modeled, changing coupling to the ablation front, P_{ablate}
- Improved LTE heat capacity for ablated matter, DCA opacity model may explain as much as 1/3 of 500 ps timing discrepancy + undesirable double-ablation front structure
- Experiments to help unravel the different effects are needed –some already in the works

There is extensive experience with a variety of ablators over many years of ICF experiments

Ablation rate data from "X-ray ablation rates in inertial confinement fusion capsule materials"
R. E. Olson, G. A. Rochau, O. L. Landen, and R. J. Leeper, Phys. Plasmas 18, 032706 (2011)

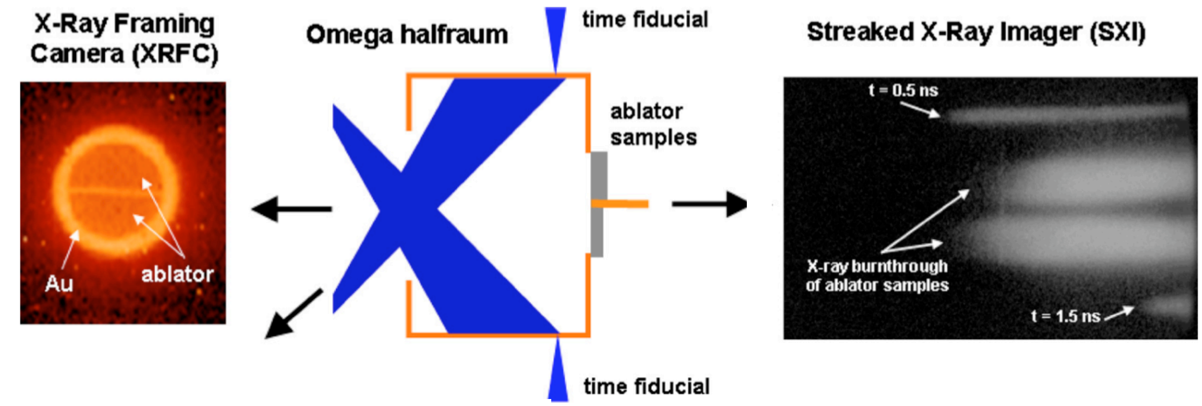
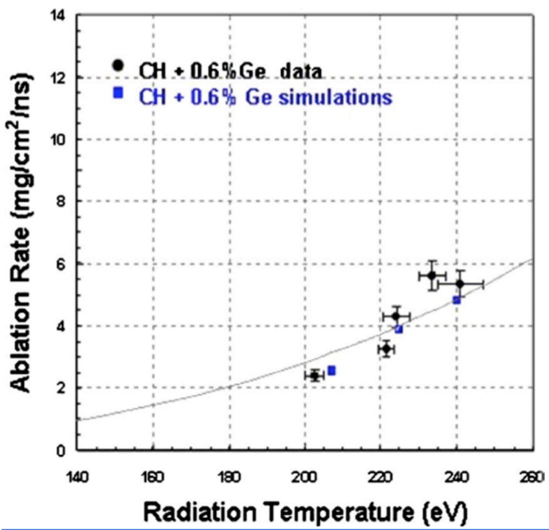
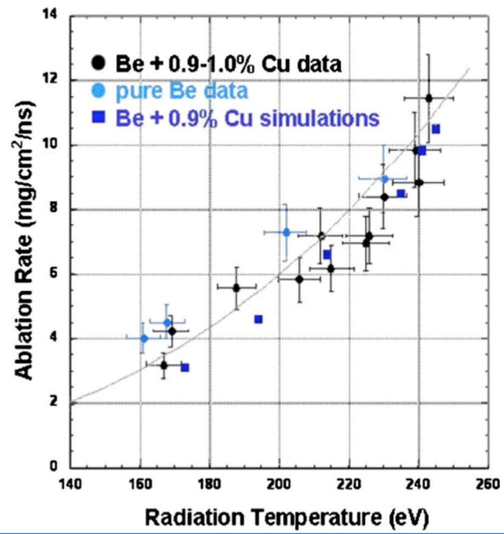
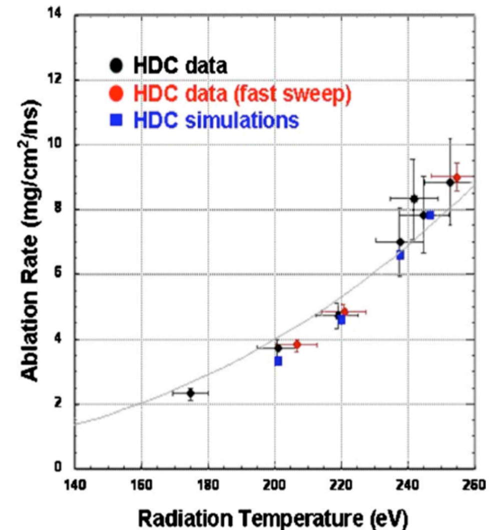


FIG. 2. (Color online) Schematic of the Omega hohlraum geometry with example SXI image of the x-ray burn-through in a pair of Ge-doped CH samples (right) and an example XRFC image viewing the samples and Au wall through the LEH.







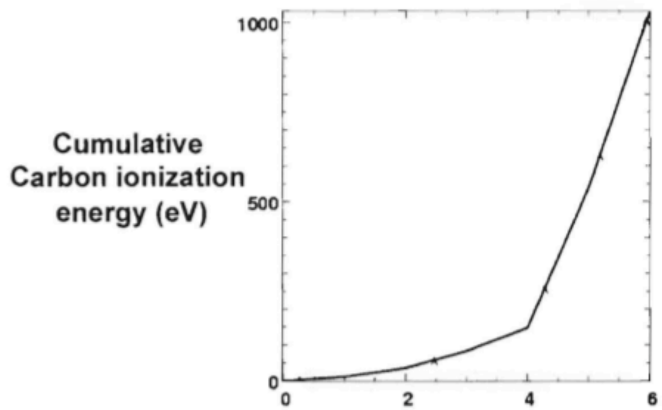
NIC implosions have much greater optical depth than earlier experiments, possibly changing ablator response

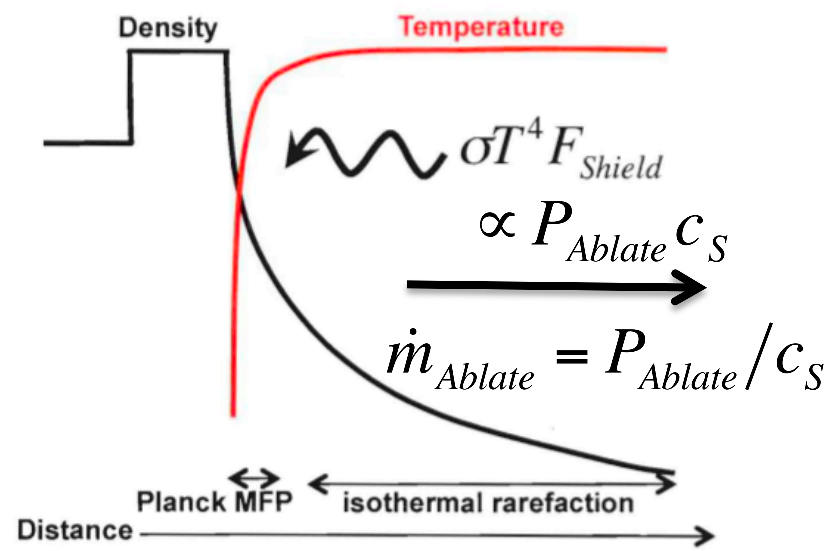
From Steve Hatchett's[1] theory of ablative x-ray drive we can see sensitivities in ablation pressure

$$P_{Ablate} = \frac{1}{1+\frac{1}{4}\left(\frac{e_{ion}}{(\bar{Z}+1)kT}\right)} \frac{\sigma T^4 F_{Shield}}{2\sqrt{\left(\frac{\bar{Z}+1}{\bar{A}}\right)kT}}$$

Shielding of the incident flux due to ablator opacity lowers P_{Ablate}

Extra energy in ionization or excitation lowers P_{Ablate}





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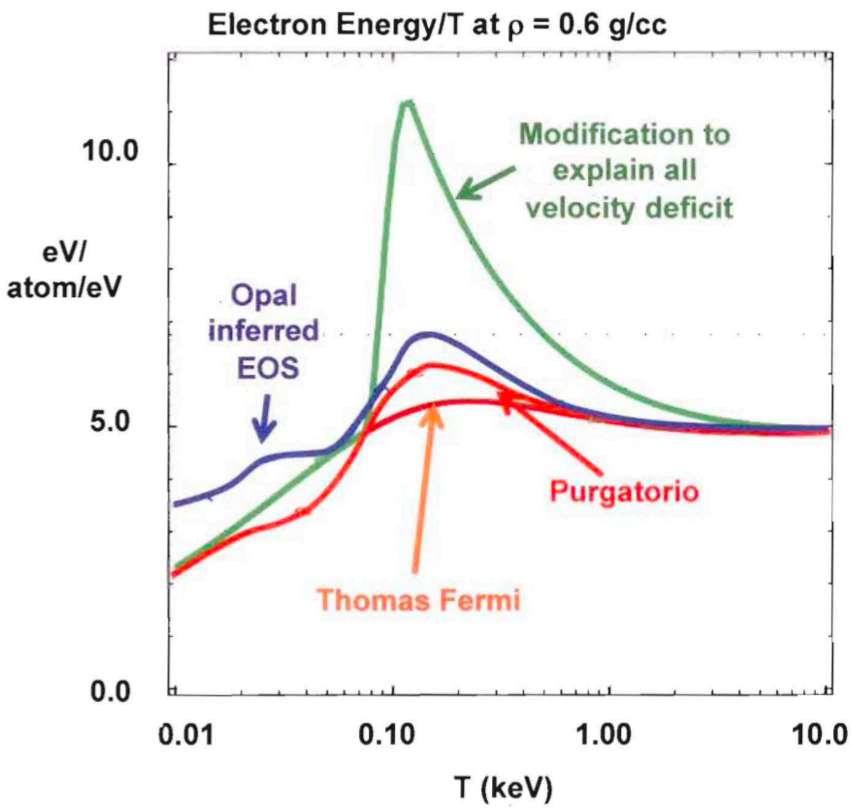
[1]S.P. Hatchett, "Ablation gas Dynamics of Low-Z materials Illuminated by Soft X-rays" UCRL-JC-108348, Sept. 6, 1991 - also summarized in Atzeni's book

Can the ablator EOS explain delayed implosion?
First attempt: modify the internal energy by adding terms to the free energy $F(T,\rho)$

- The nominal Thomas- Fermi equation of state seemed surprisingly devoid of shell structure as carbon burns through the K-shell



- Better EOS's do show modest increase in energy in C K-shell regime, but required modification is implausible -
- Purgatorio EOS adds about 70 ps to implosion time vs. 500 ps discrepancy
- Modified EOS also thickens the shell – closer to the ConA data

NLTE holds when radiative transition rates are faster than collisional rates - could this affect ablator EOS/opacity?

- **Collisional rates** $\propto n_e^2$
- **Radiative rates**

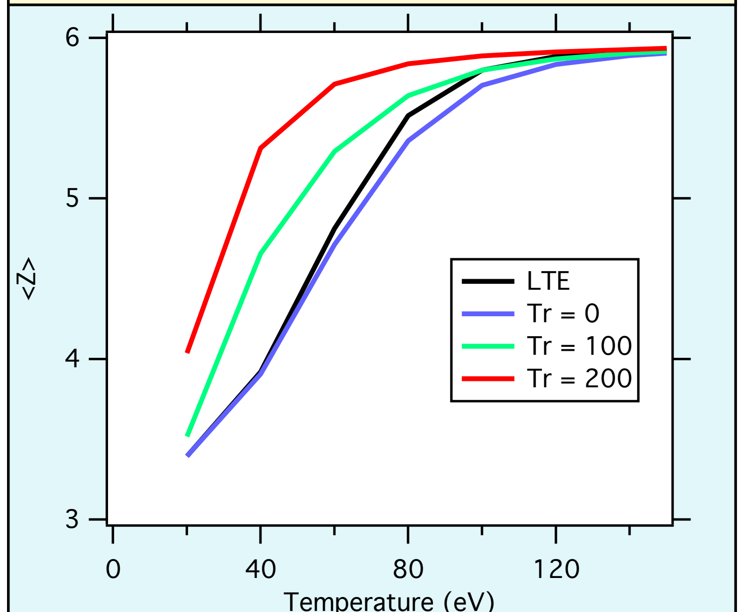
  Spontaneous rates $\propto \Delta E^2$

  Stimulated rates $\propto J_\nu$

⇒NLTE effects appear for low densities, high radiation fields, and / or large transition energies

Material properties depend on density, temperature, photon spectrum and time

Carbon <Z> : ρ = 0.01 g/cm³



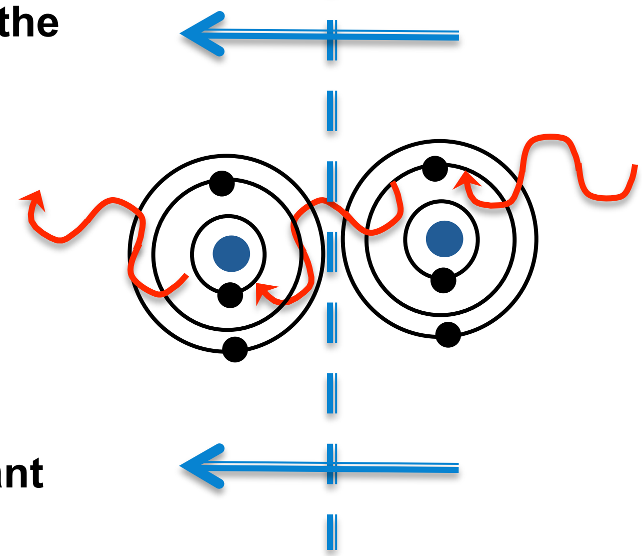
Radiation drives the material away from LTE

For a significant portion of NIC implosions, there is an extended low T_e (<120eV) low density (<.1 g/cc) CH atmosphere that is NLTE. Does it matter?

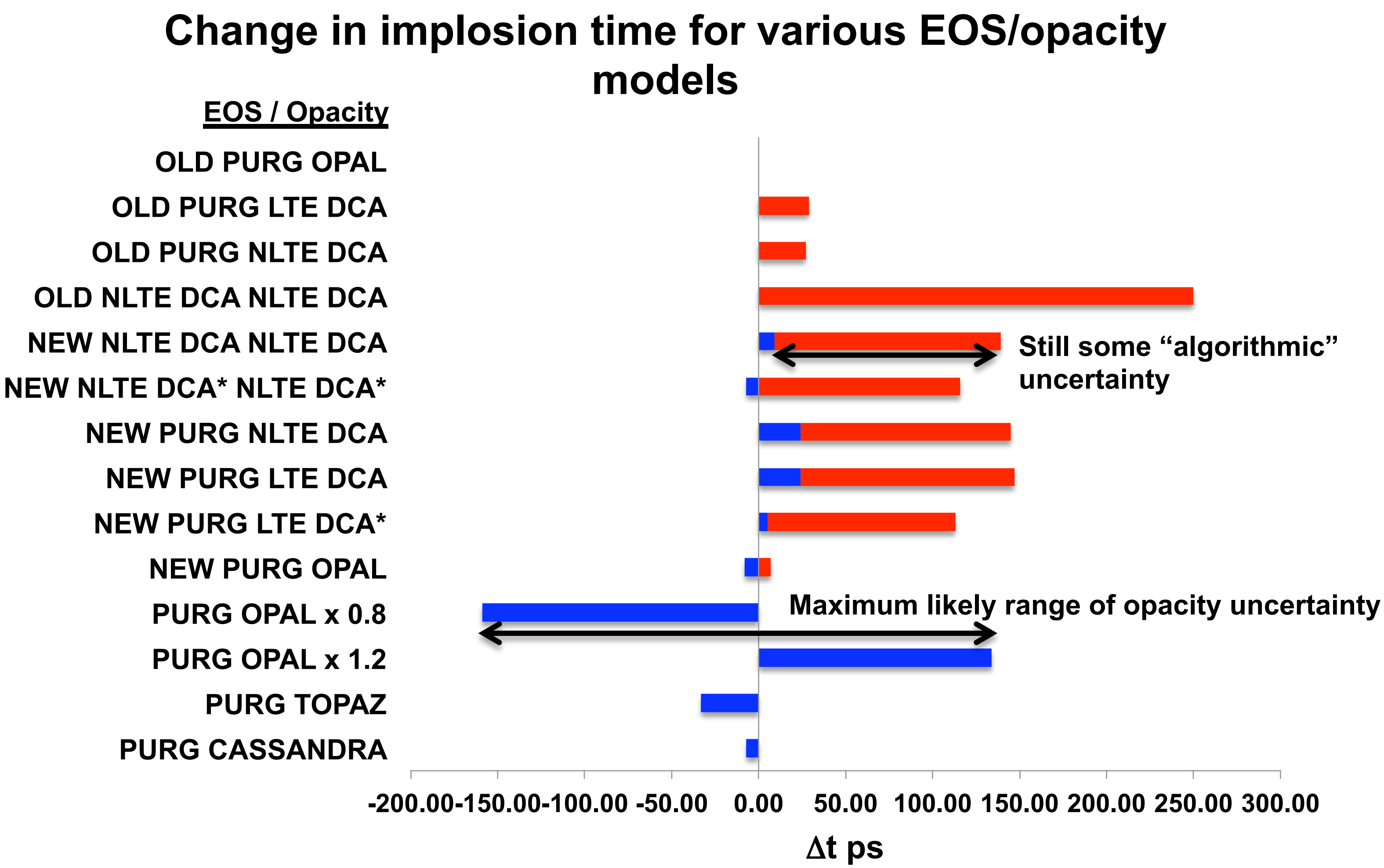
The NLTE properties of the NIC ablator "broke" the code

- **The problem of radiation transport through a NLTE plasma that is radiatively driven, where the opacity and radiation field depend on a self-consistent solution of the atomic populations, is challenging**
- ***Symptom*: code would not give good energy conservation together with accurate solution for T_e**
- ***Solution*: Iterate the radiation transport solution to ensure accurate $E(J_\nu)$, $n_e(J_\nu)$**
- ***Result*: modest effects on capsule model, but significant new code capability established**

Radiation flux is "filtered" by atmosphere



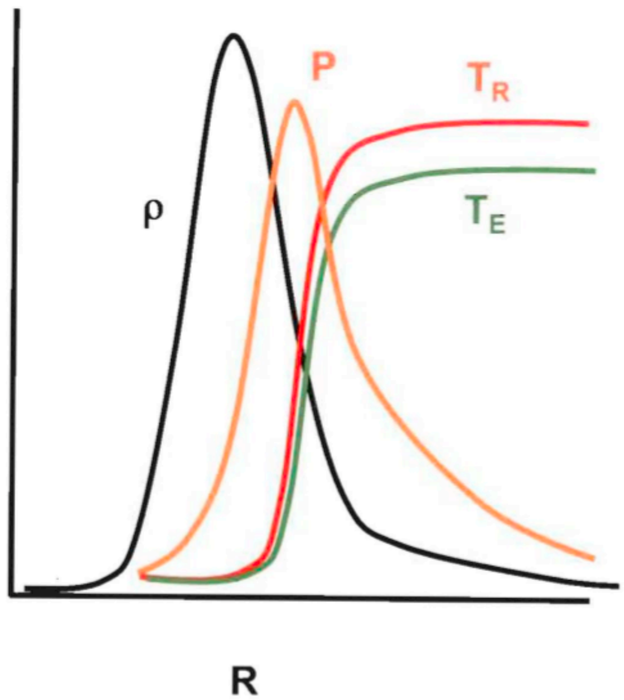
The new iterative radiation solve gives small LTE-NLTE difference in implosion timing, but there remains significant uncertainty due to EOS /opacity



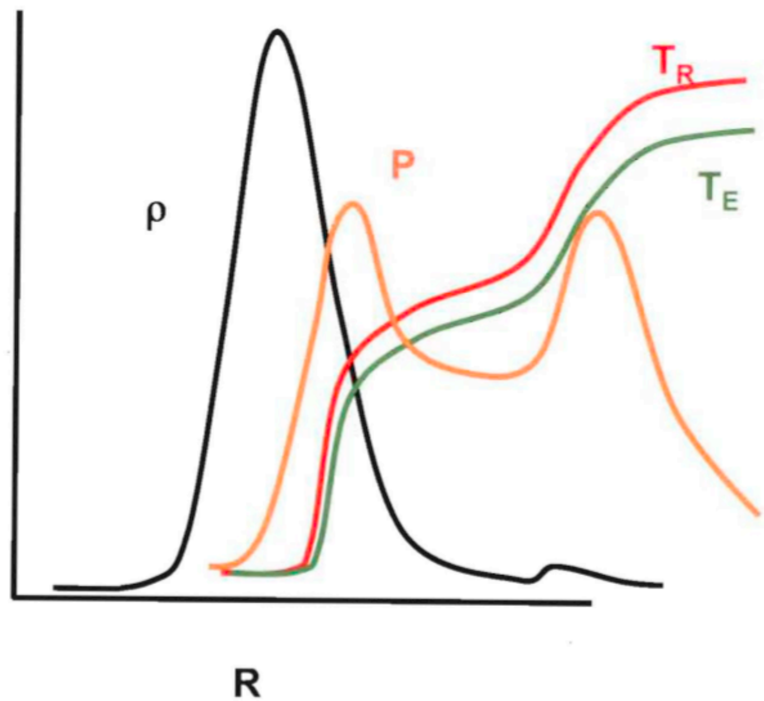
PURG = Purgatorio LEOS 5370
DCA = inline default DCA   DCA* = detailed Carbon model #3

A feature of the DCA models: double ablation front exists between times ~ 14.5 -16.5 ns, lowering pressure at capsule

Usual (LTE-Opal) picture



DCA picture

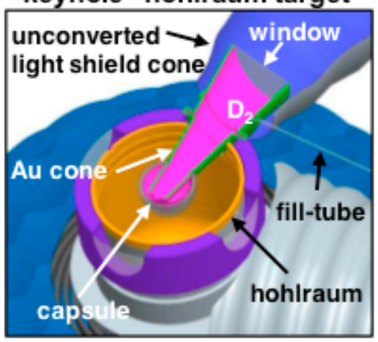


- Outer ablation front catches up by 17 ns, might be implicated in extra shock
- Old NLTE model had much more pronounced version of double ablation front
- If real, a double ablation front could affect shocks after the second

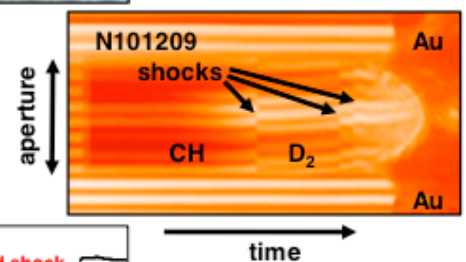
Ignition campaign diagnostics characterize shocks in the fuel as well as shell properties, partially constraining models

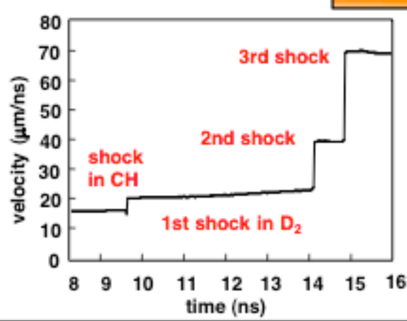
VISAR "keyhole"

"keyhole" hohlraum target



fringe shifts proportional to shock speed



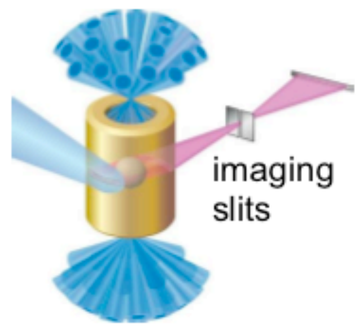


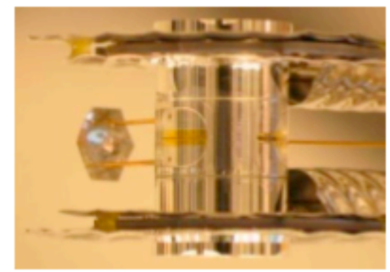
Measures shock velocities and merger times

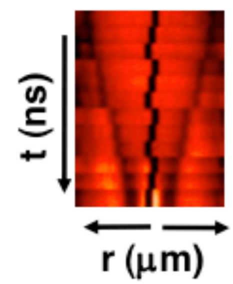
Convergent Ablator (ConA)

Backlit D-^{3}He-filled capsule between R ~200-500 μm
1.0-1.4 MJ hohlraum drive

Gated 9 keV X-ray radiography

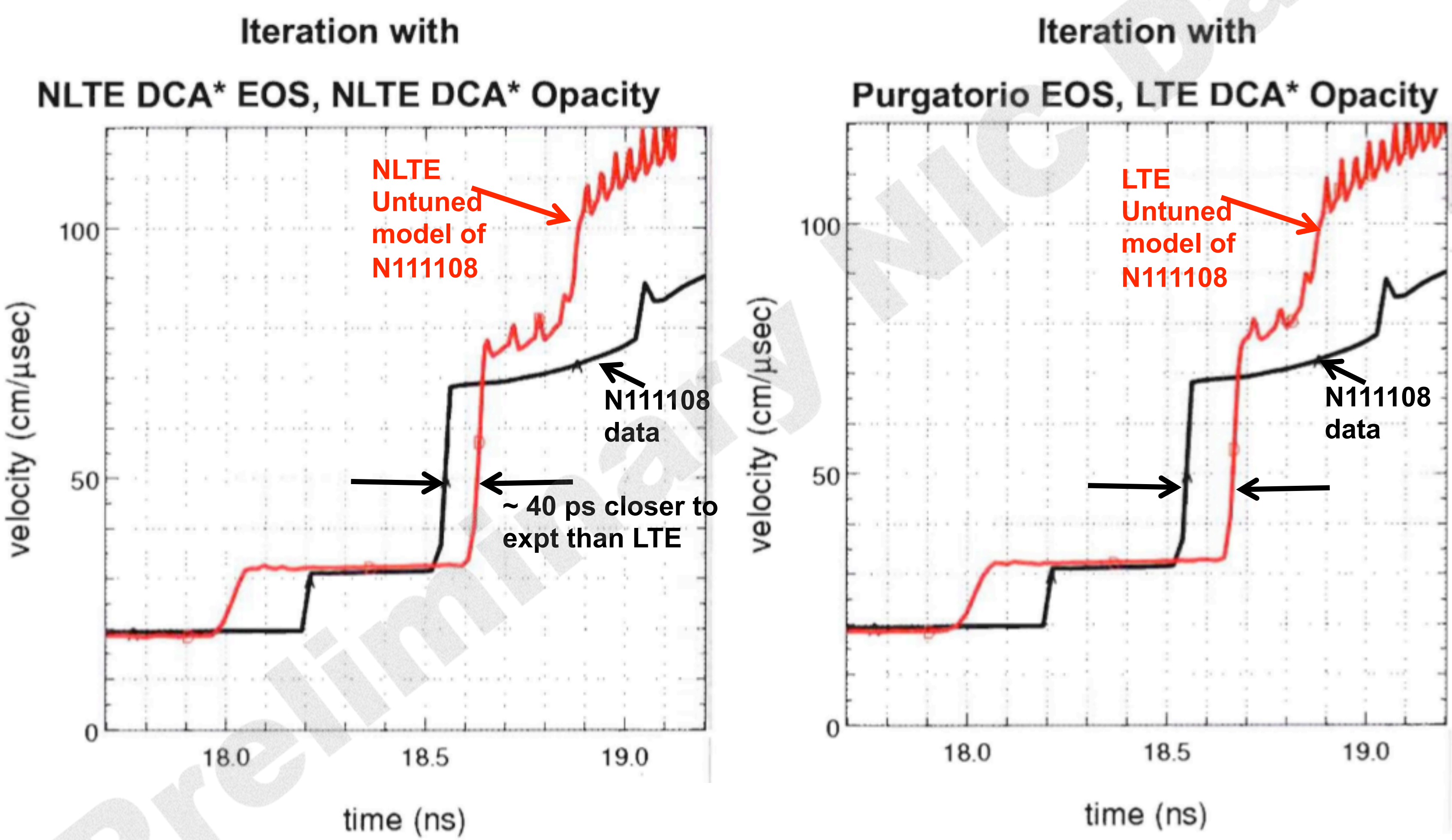






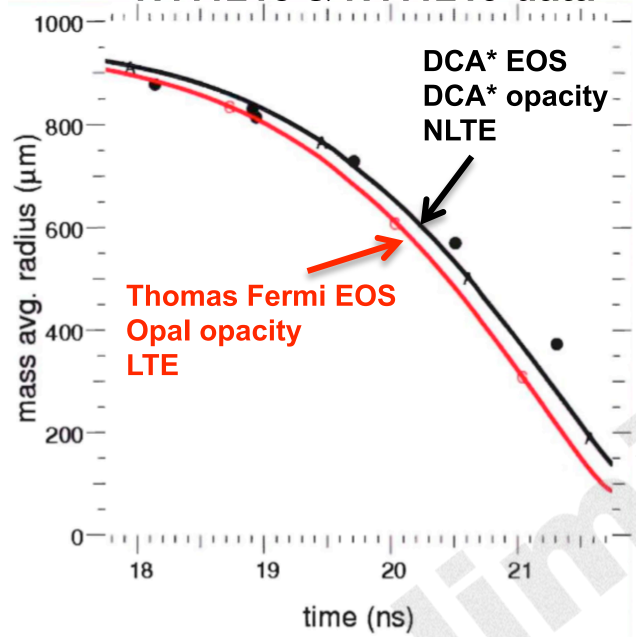
Measures shell velocity, density thickness, and remaining mass

The NLTE model can affect 3rd shock timing

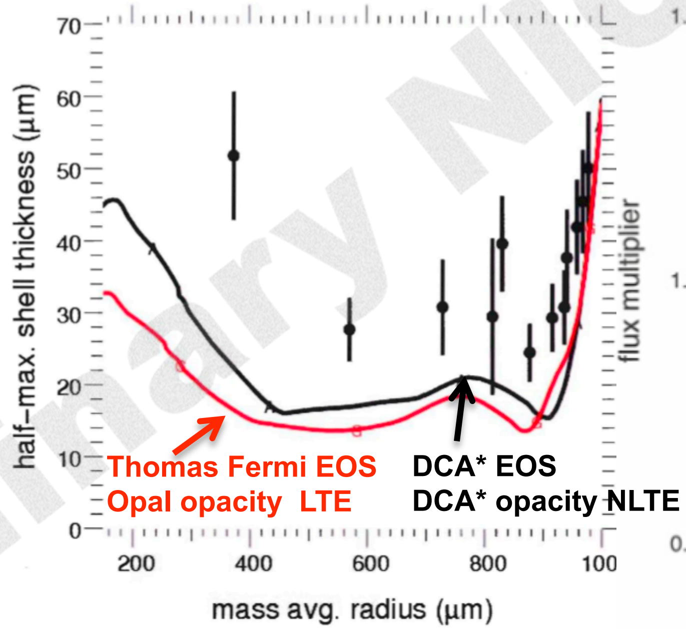


Discrepancies between code and experiment in the “1D” hydro need to be resolved to improve 2-D and 3-D predictions of implosion performance

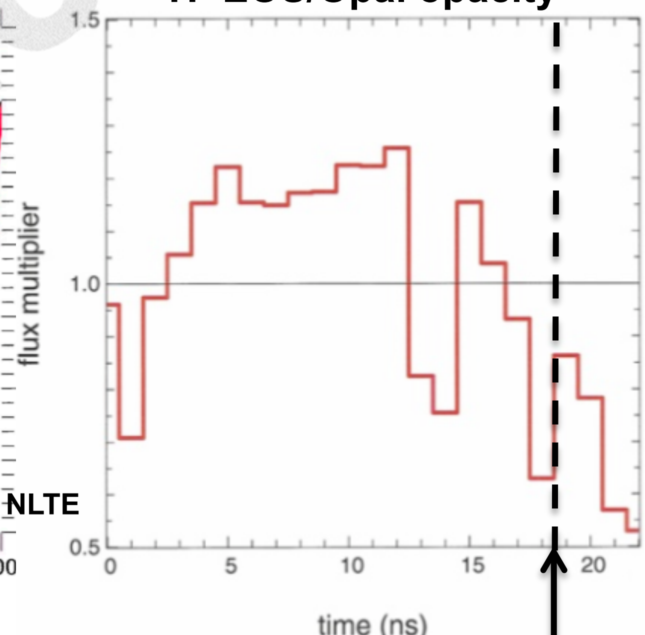
Radius vs time
simulated ConA with nominal drive
N111218 & N111219 data



Shell thickness vs. R
N111218 & N111219 data



Drive multiplier required to match 1-4 shock timing and trajectory for N120131 with TF EOS/Opal opacity

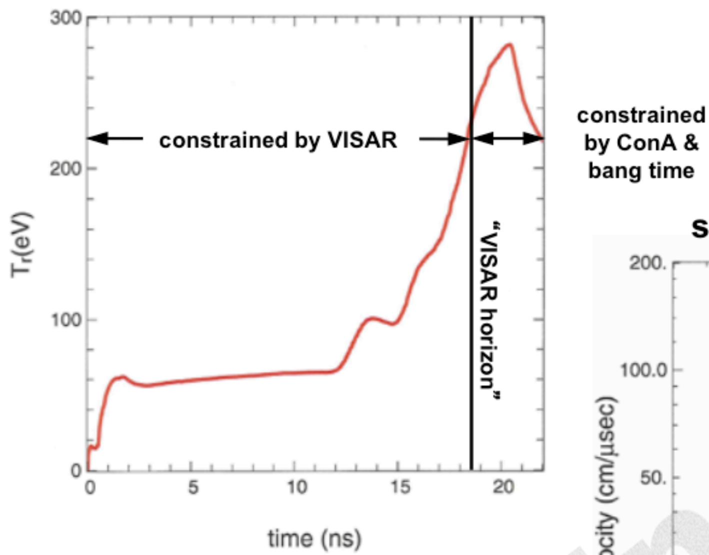


Low stagnation pressure – largest discrepancy with models and very bad for capsule performance - suggests that the drive, ablator or fuel properties are causing an extra, entropy-raising shock in the fuel

Visar “horizon” caused by loss of reflection means late-time drive less constrained

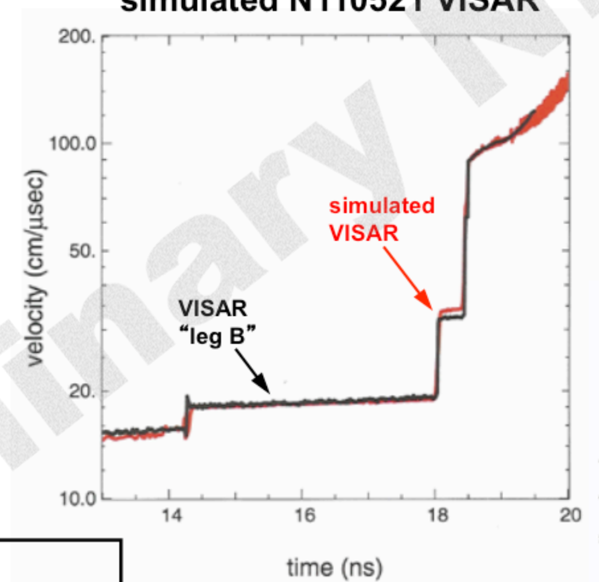
Dan Clark and Denise Hinkel have used post-shot drive adjustments to try to match Visar and ConA data

N110608 tuned radiation drive



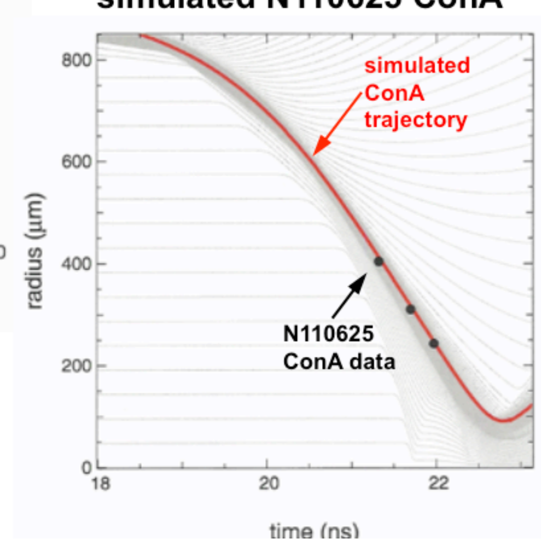
Simulations also match as much as possible velocity, remaining mass, shell thickness, and density

simulated N110521 VISAR



Thomas Fermi EOS and Opal opacity used throughout

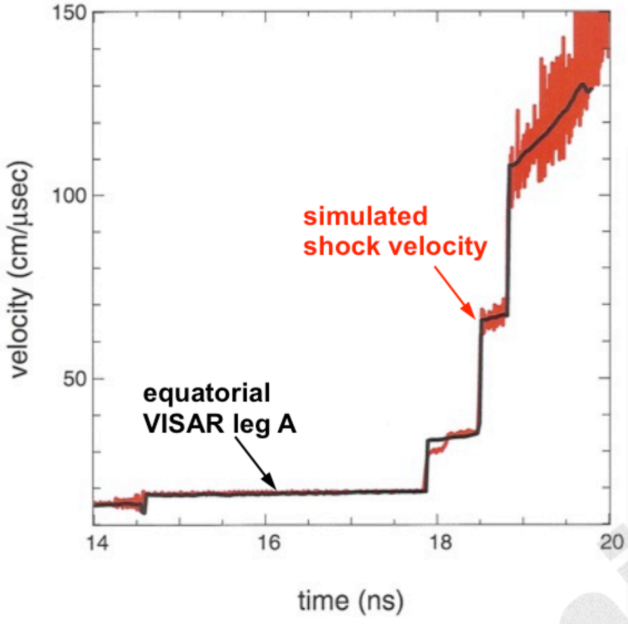
simulated N110625 ConA



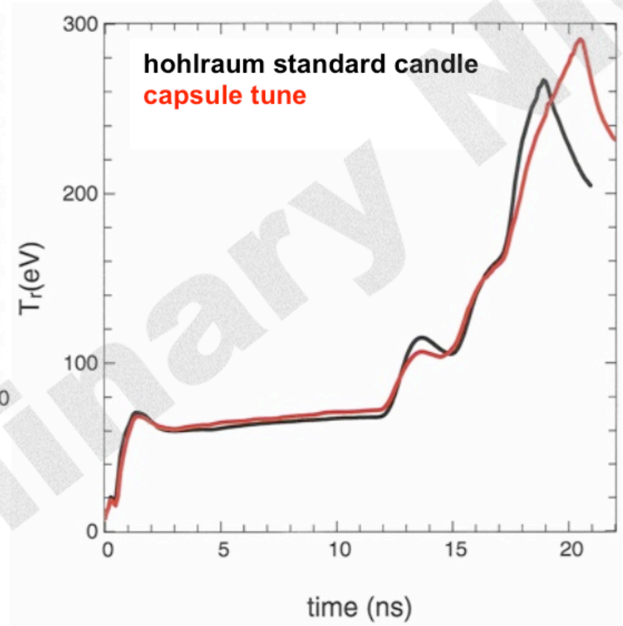
Flux ratios from post-shot hohlraum simulations are used to account for differing backscatter or laser performance between VISAR and ConA shots

Drives for 1ns (fast) and 3ns (slow) rise shots have been generated – this slide shows fast rise N120106

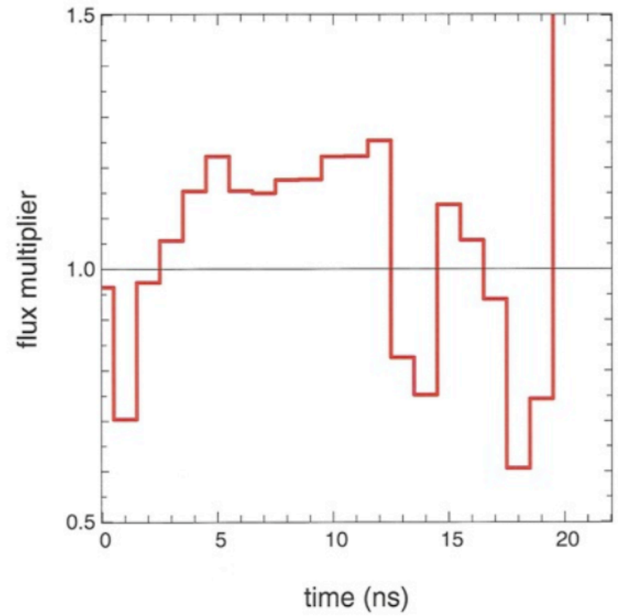
Visar



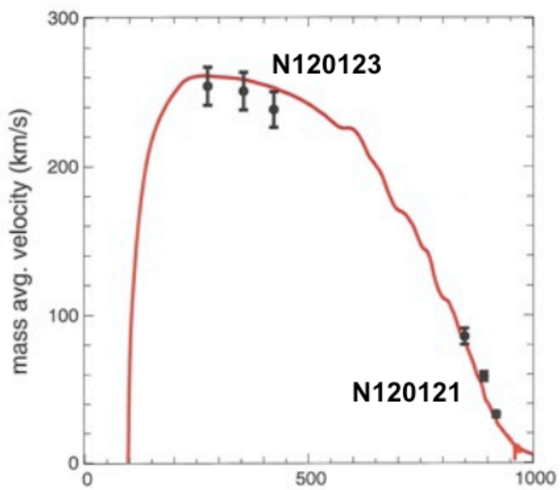
Radiation drive

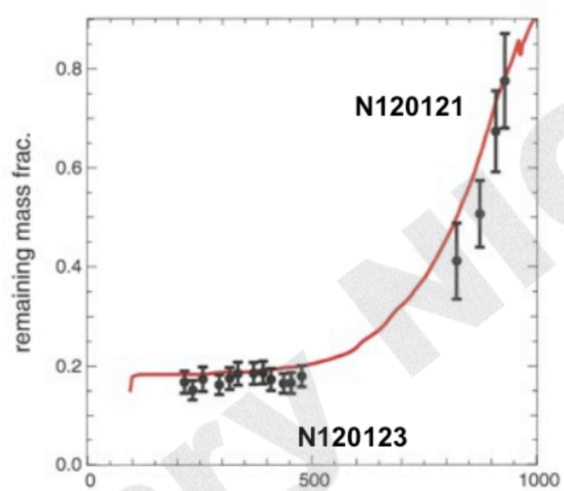


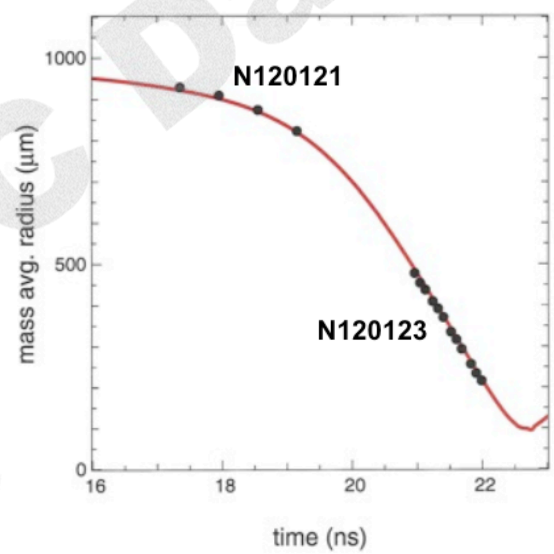
Radiation flux multiplier

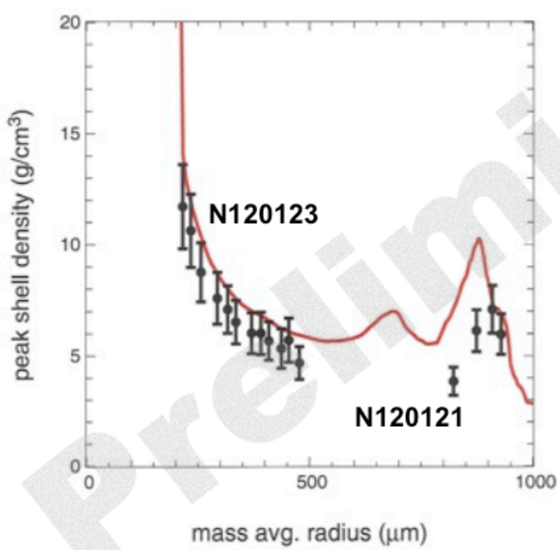


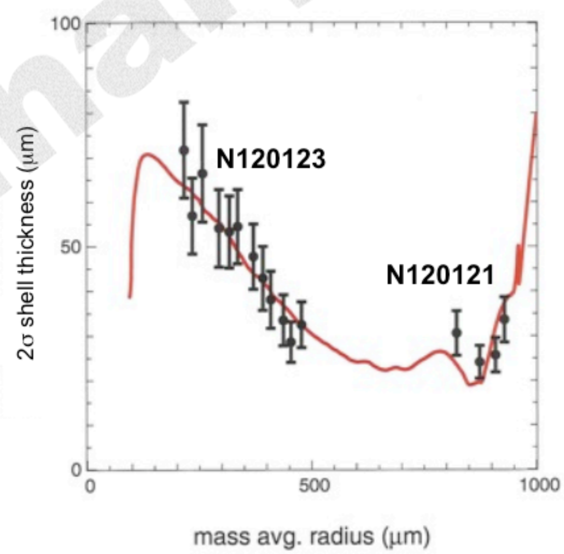
Drive adjustments alone match nearly all of the associated Jan. ConA observables fairly well





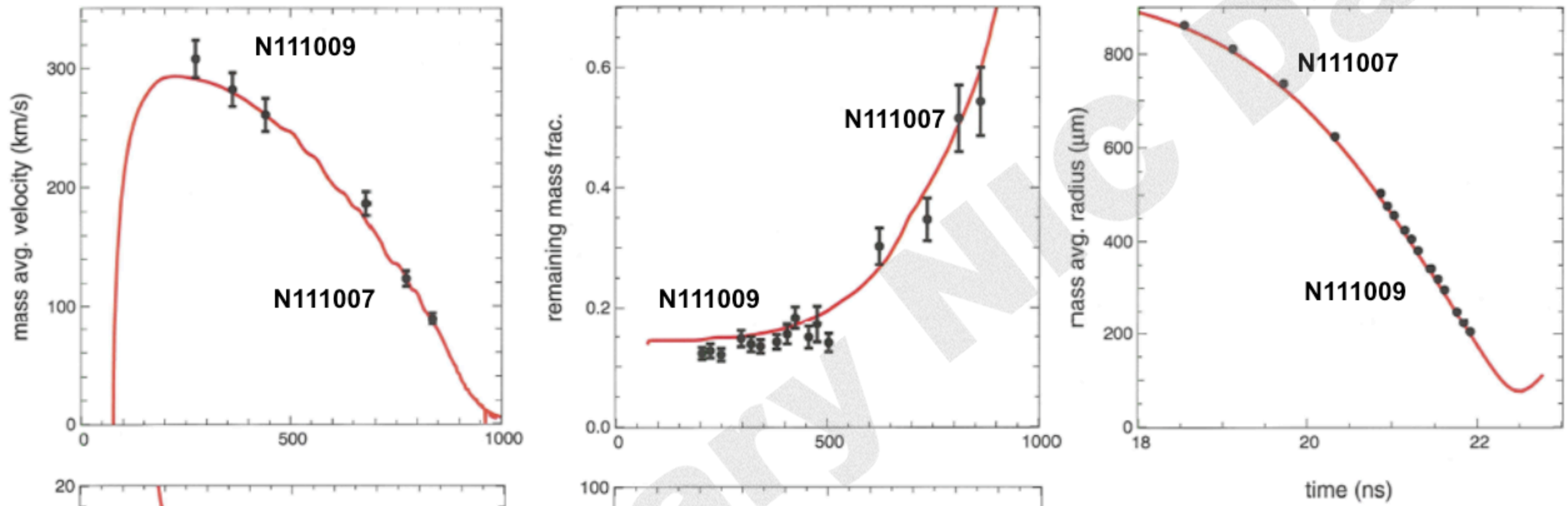


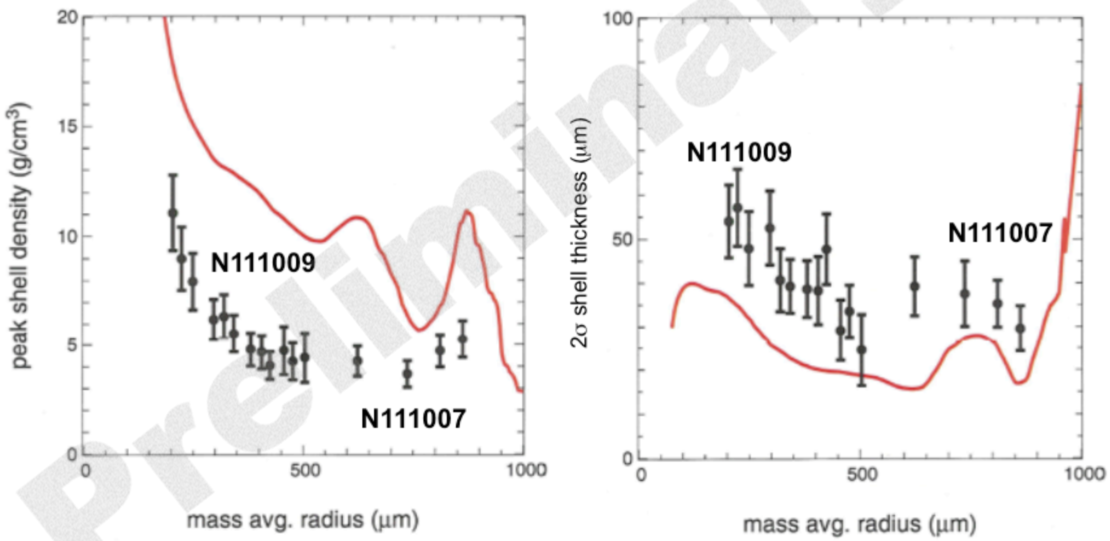




shock flash (ns)	bang time (ns)
??.??±0.2	22.57±0.07
21.63	22.53

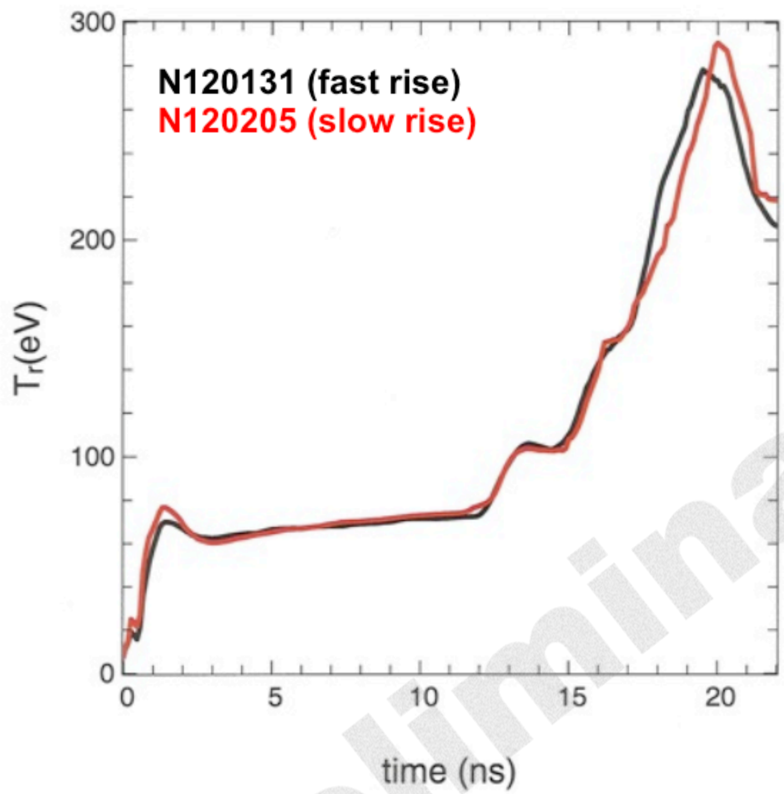
Previous comparisons to Oct. and Dec. data (with drive adjustments alone) were not nearly as close

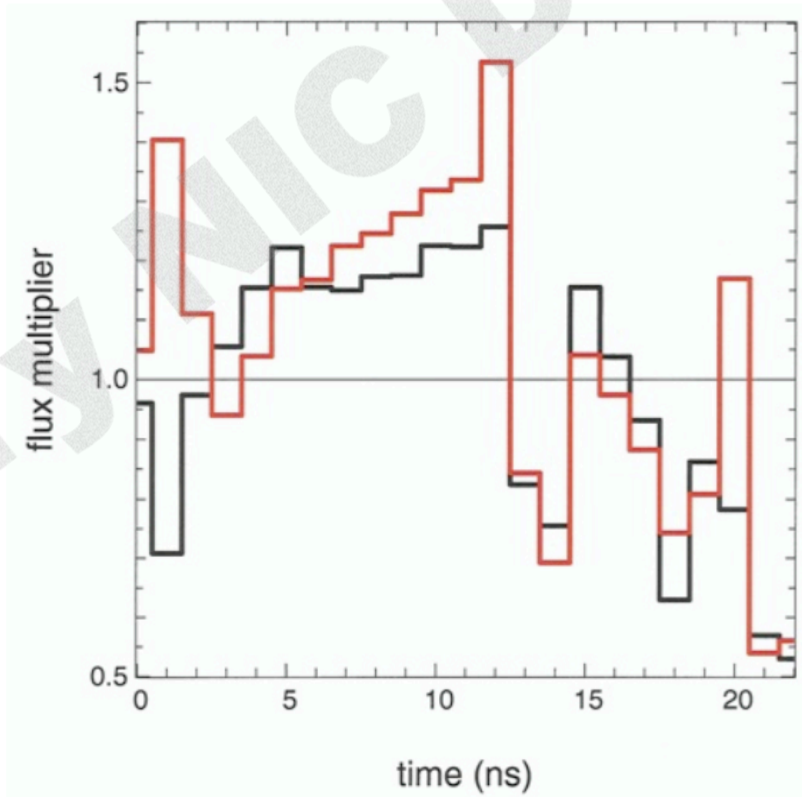




shock flash (ns)	bang time (ns)
21.05 ±0.2	22.36±0.07
21.62	22.35

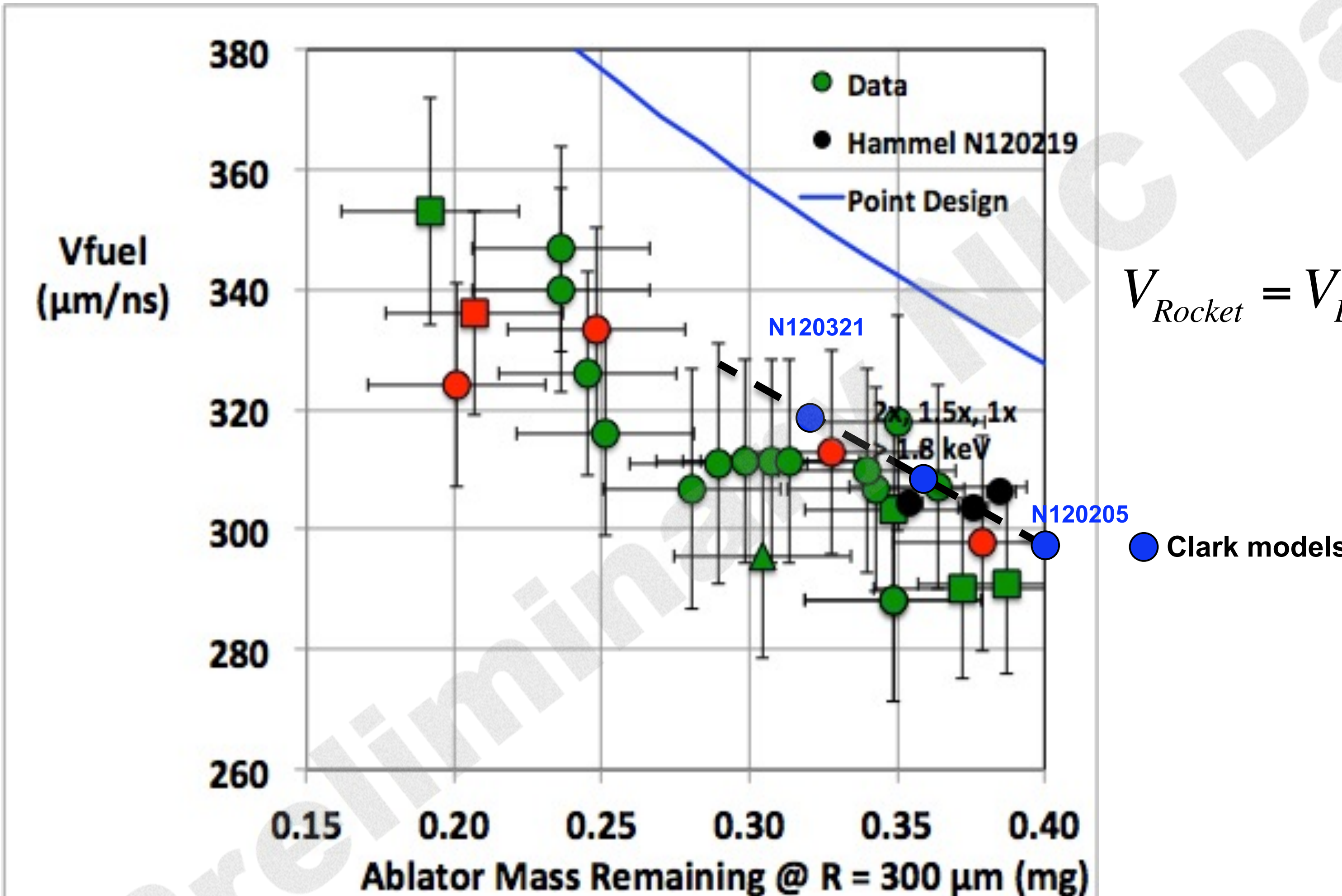
The DT tune for the fast rise requires a decrement of ~80% followed by a quick falloff - similar for slow rise but from a higher peak in that case





* preliminary — slow rise VISAR tune (N120108) is still being revised

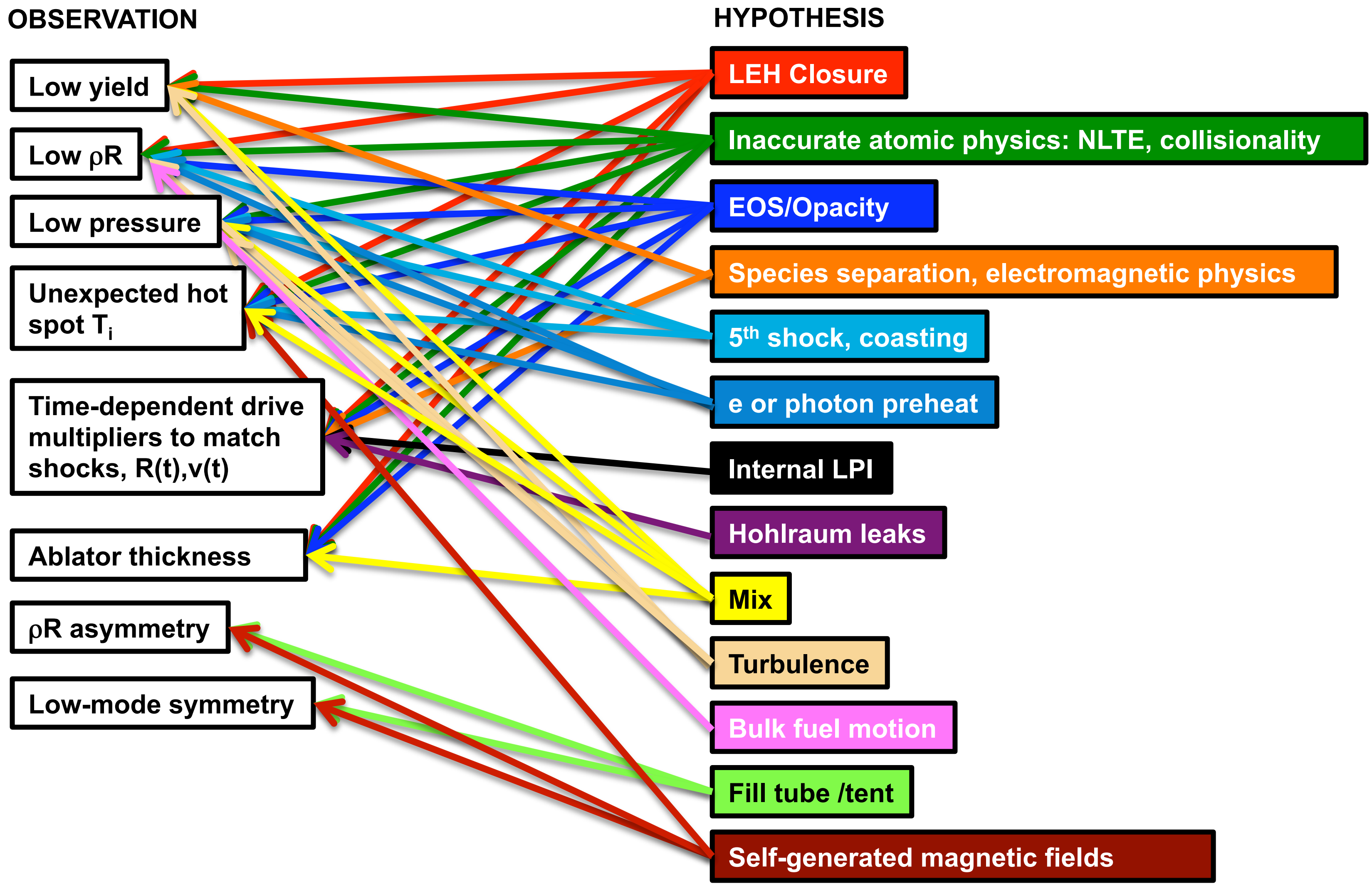
Another question– how well is the capsule obeying the rocket equation with the expected exhaust velocity?



$$V_{Rocket} = V_{Exhaust} \ln\left(\frac{M_0}{M}\right)$$

The data is from near the end of the implosion – can we accurately measure the remaining mass at that point?

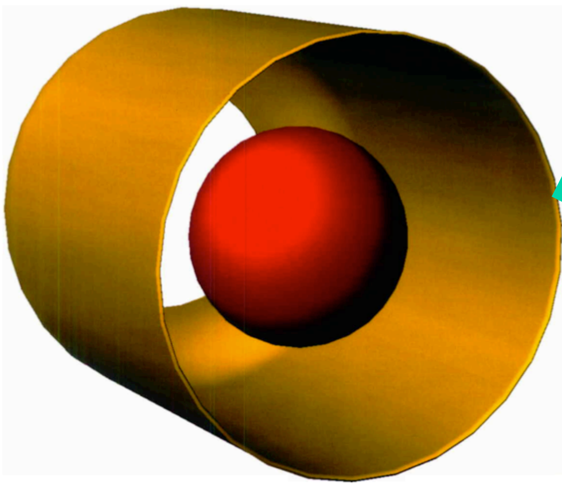
Almost every NIC observation can be related to multiple hypotheses



Can we design experiments to isolate and prioritize effects?

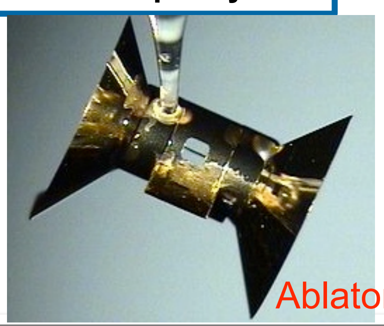
Some experiments are already planned to measure and understand discrepancies in the current ignition platform 1D implosion system

- Measure hohlraum emission directed at capsule
- Measure LEH closure
- Update hohlraum/LPI model



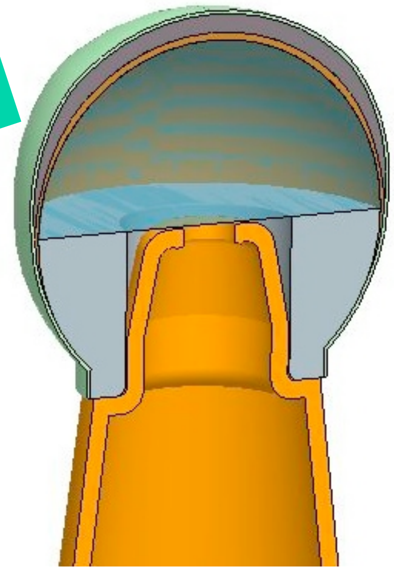
View Factor

- Measure ablator opacity



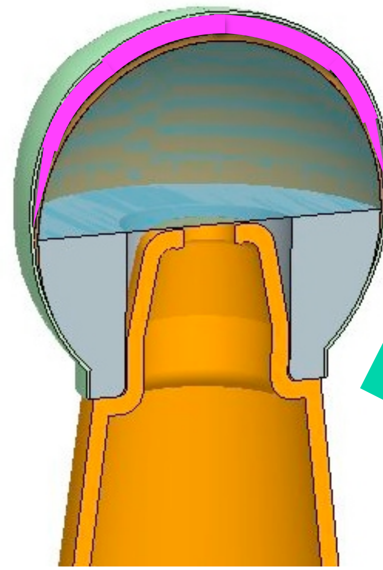
Ablator Opacity (Omega)

- Measure x-ray drive at capsule surface
- Confirm updated model reproduces Al drive pressure



Crystal Ball (Al)

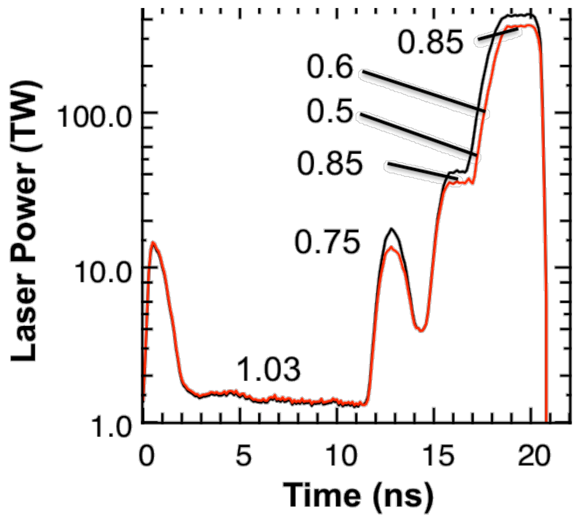
- Measure ablation pressure of known drive into GDP
- Evaluate other ablator candidates (Be, B_4C,…)

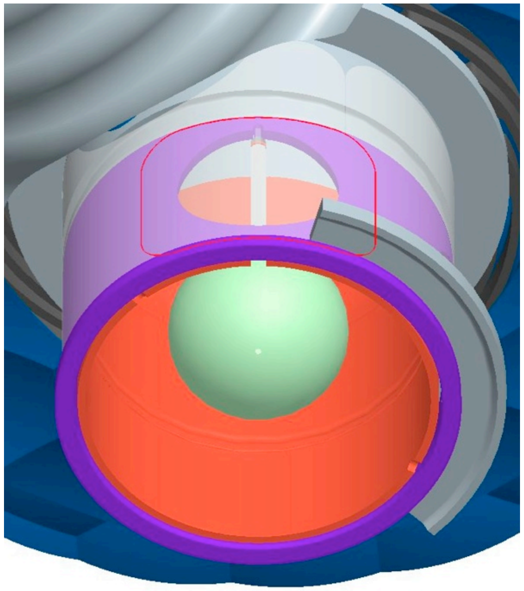


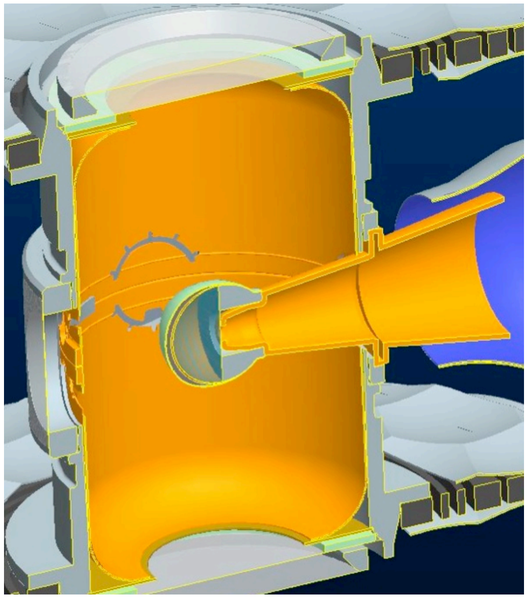
Crystal Ball (GDP)
Crystal Ball (Alt Abl)

On to mix
…

The Viewfactor and Crystal Ball experiments use NIF-Qualified diagnostics

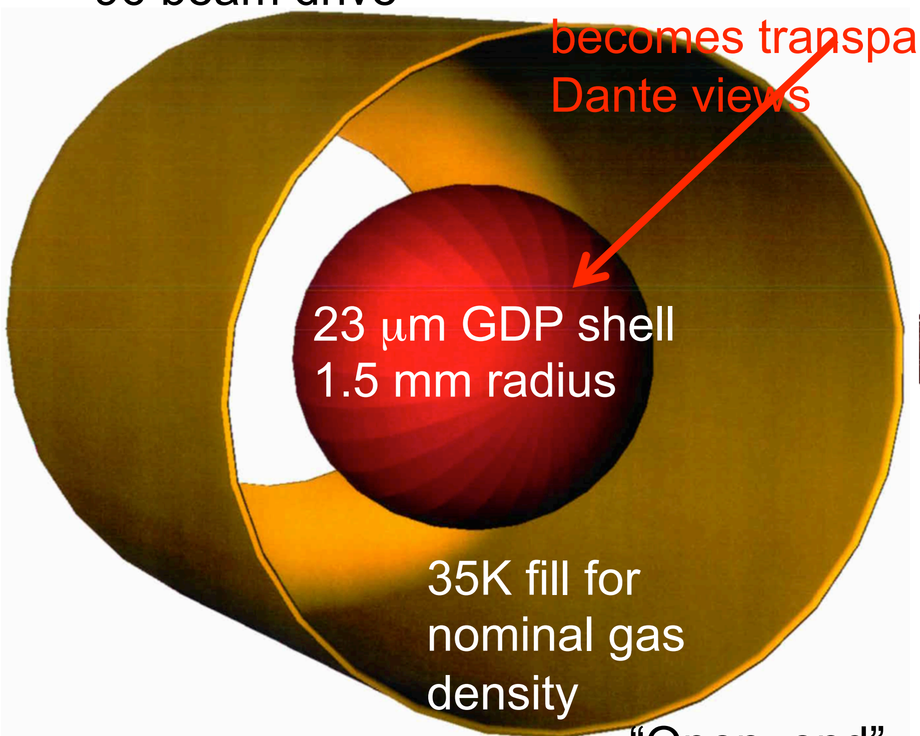


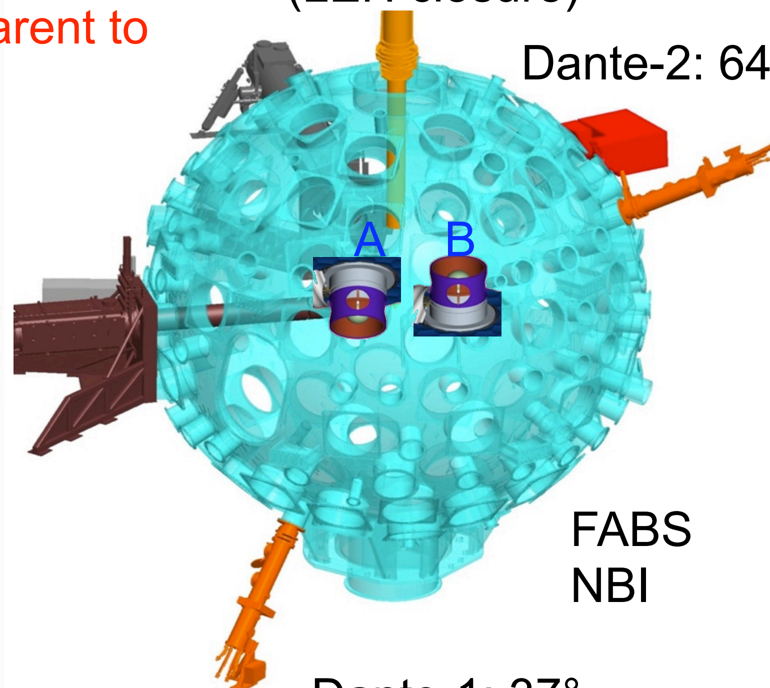




Primary Diagnostic	Dante (1 & 2)	VISAR
Diagnostic uncertainty	+/- 5% Power	+/- 1% velocity
Required uncertainty	+/- 7.5% Power	+/- 3.4% velocity

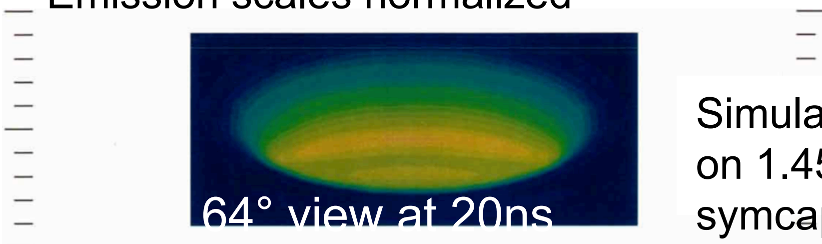
The Viewfactor target exposes the internal hohlraum drive to a suite of NIF diagnostics

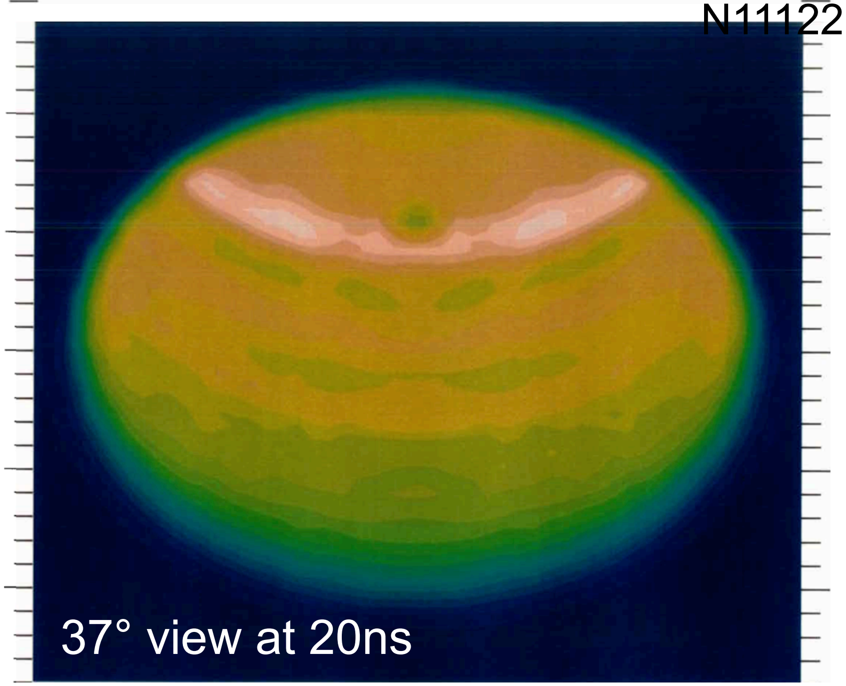




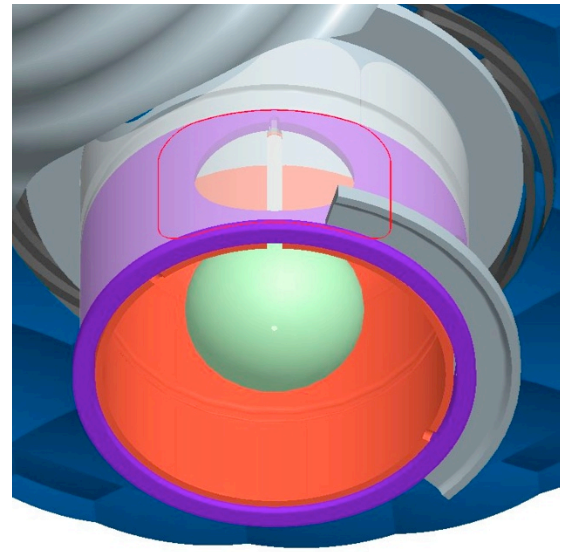
Type A target points open end toward Dante 1 (37°)

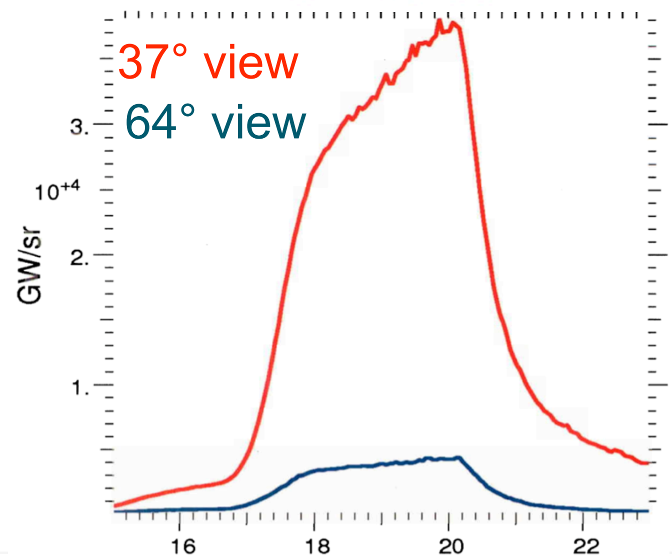
Emission scales normalized





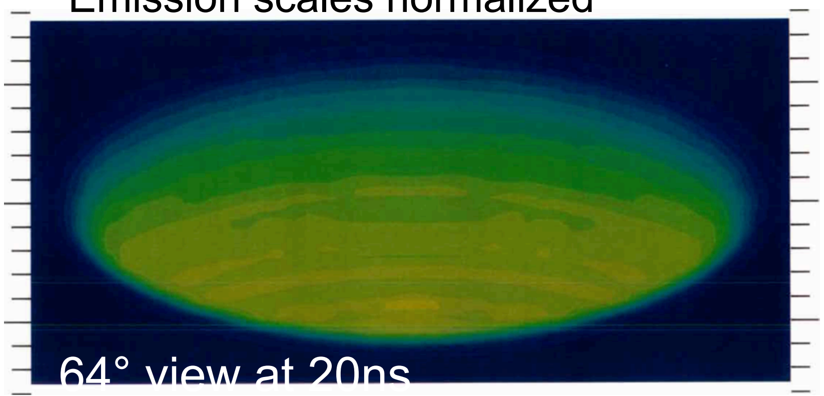
Simulation based on 1.45MJ U symcap: N111221



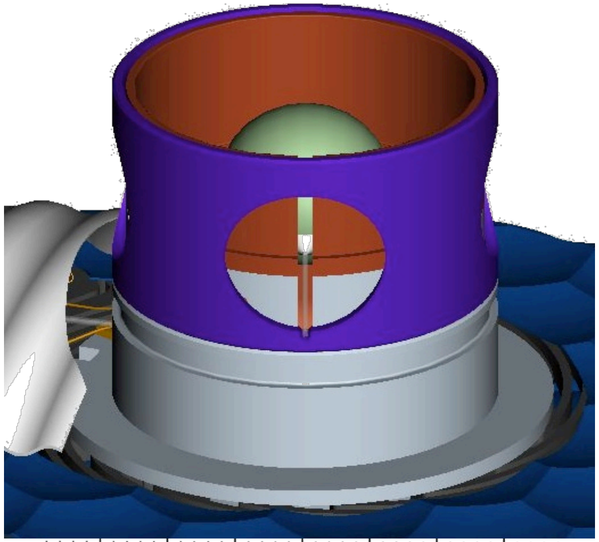


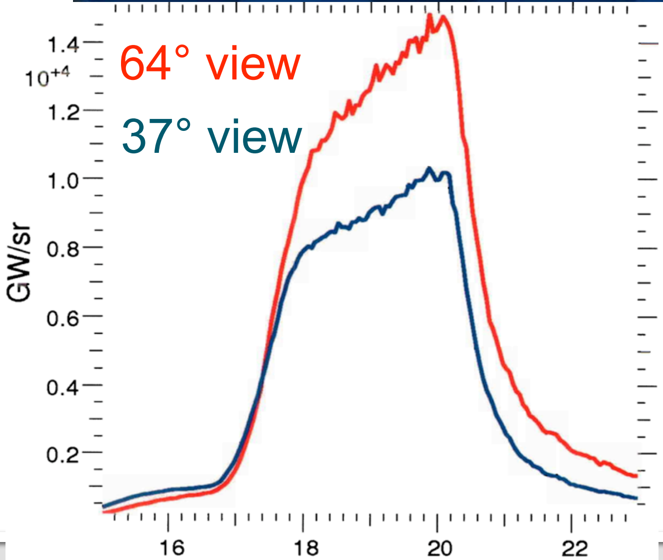
Type B target points open end toward Dante 2 (64°)

Emission scales normalized

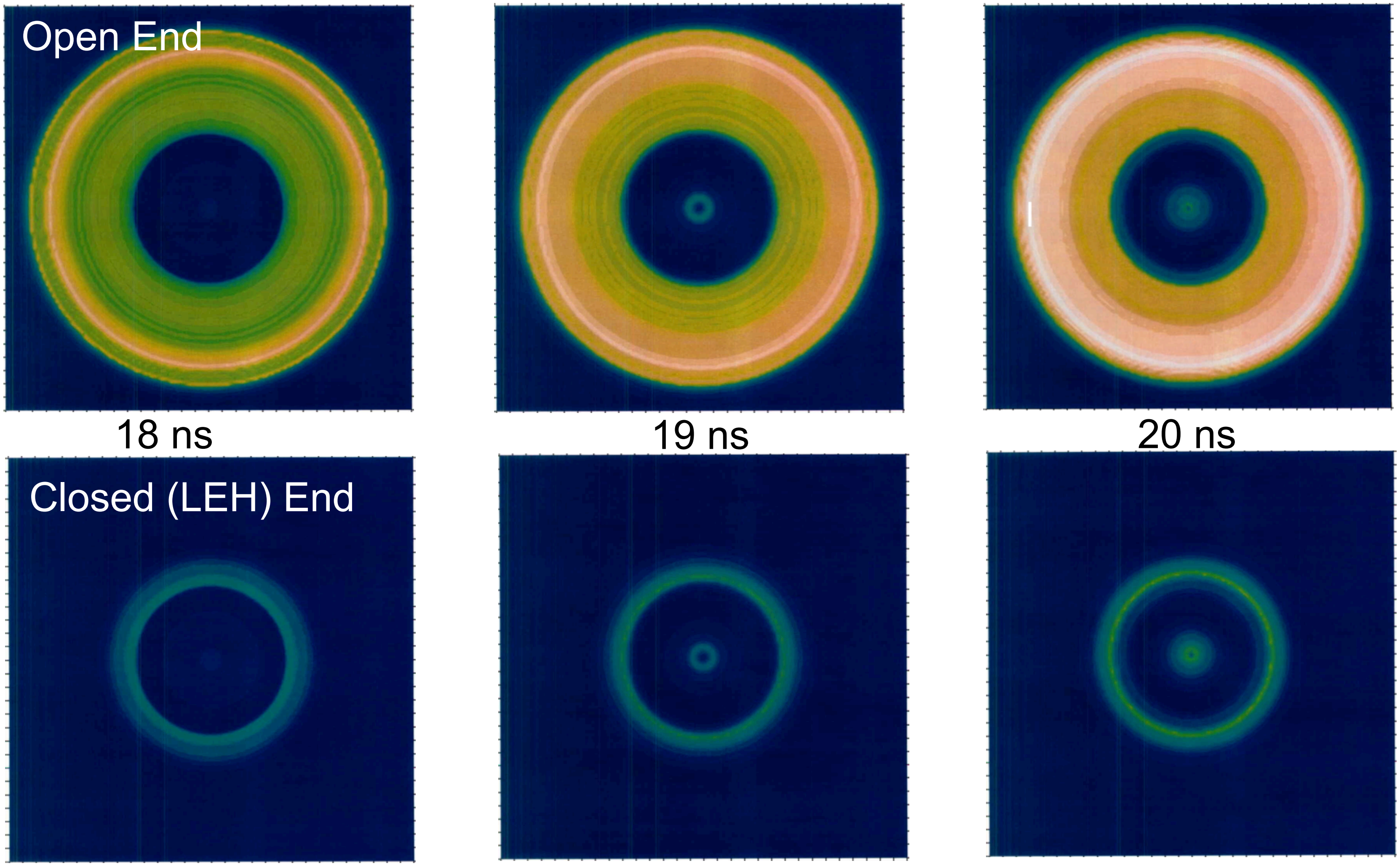


Backscatter and cross-beam transfer calculated for closed end beams only





Framing camera images from the polar DIM deliver a complete time-resolved characterization of the LEH closure



This data is crucial to accurately correct ignition target Dante measurements

The Crystal Ball delivers a high accuracy drive pressure measurement for the entire pulse duration

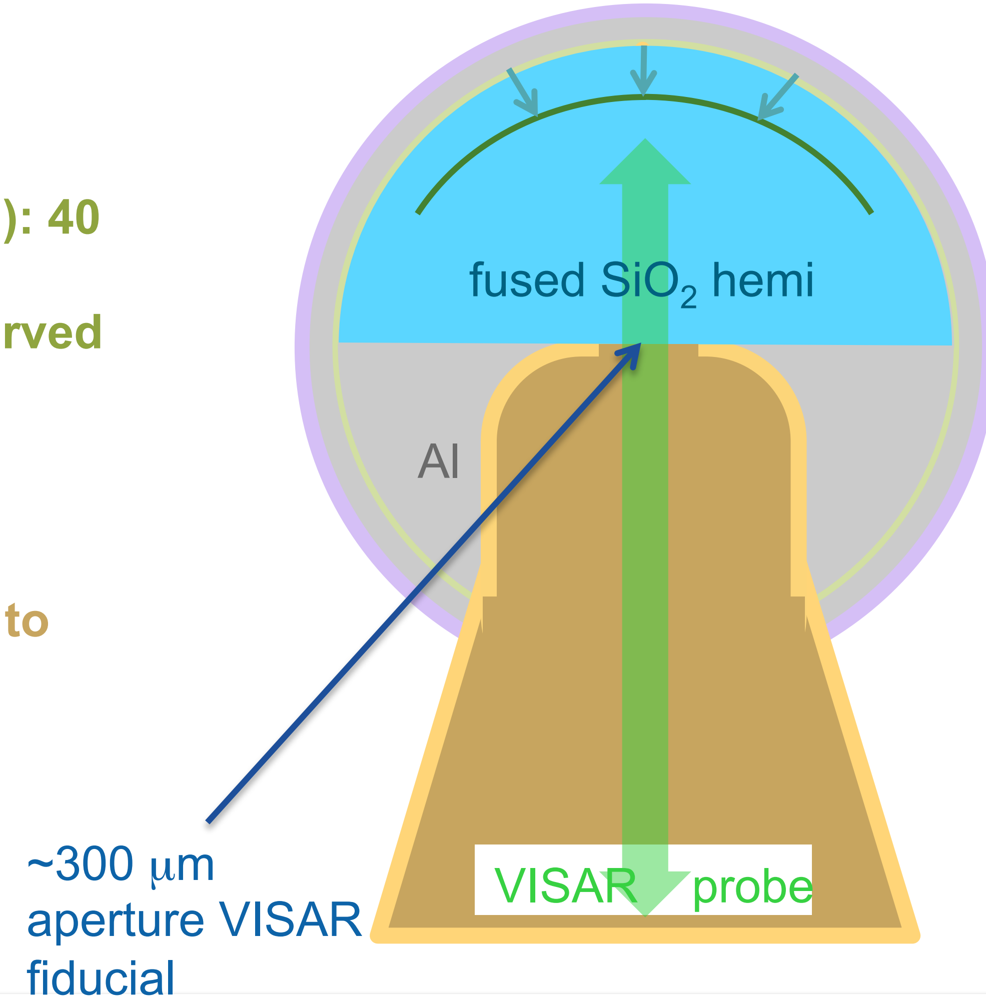
CH coating: 23 +/-3 μm

Al: 100 +/- 2 μm

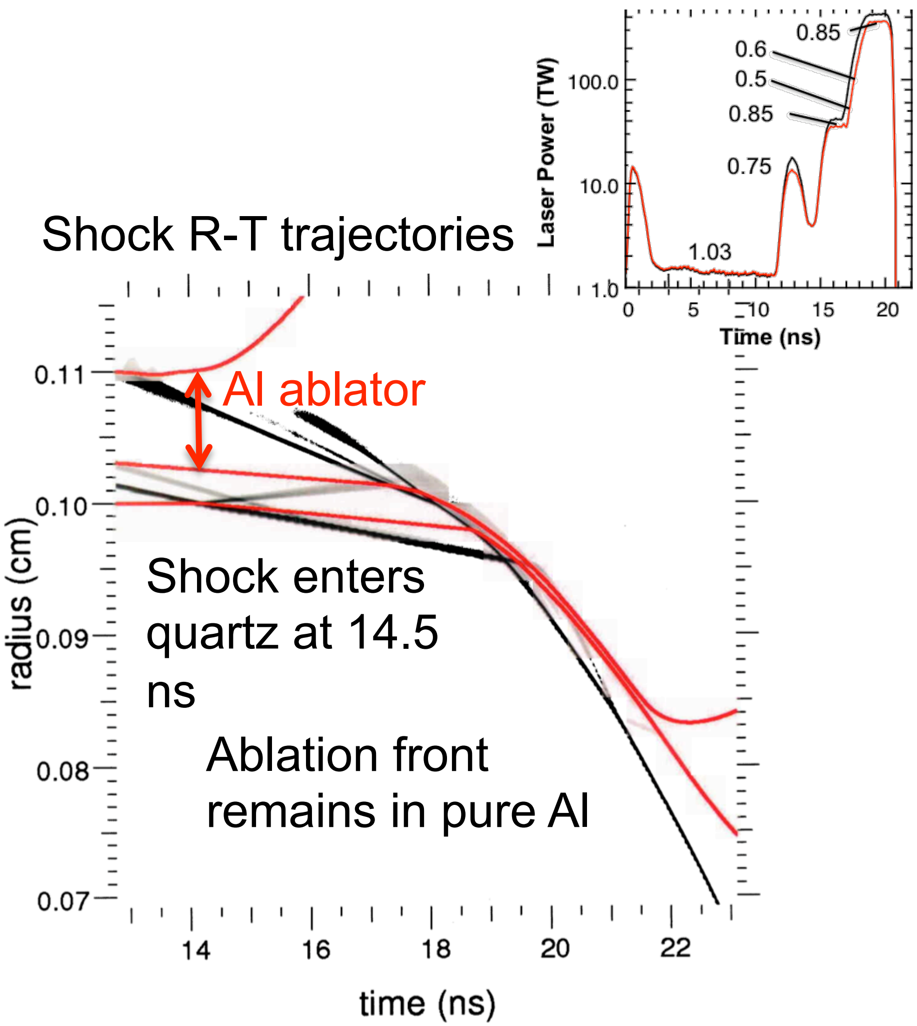
Doped Al (4.0 +/- 1.0 wt% Au): 40 +/- 5 μm
(keep M-band to levels observed in quartz at Omega)

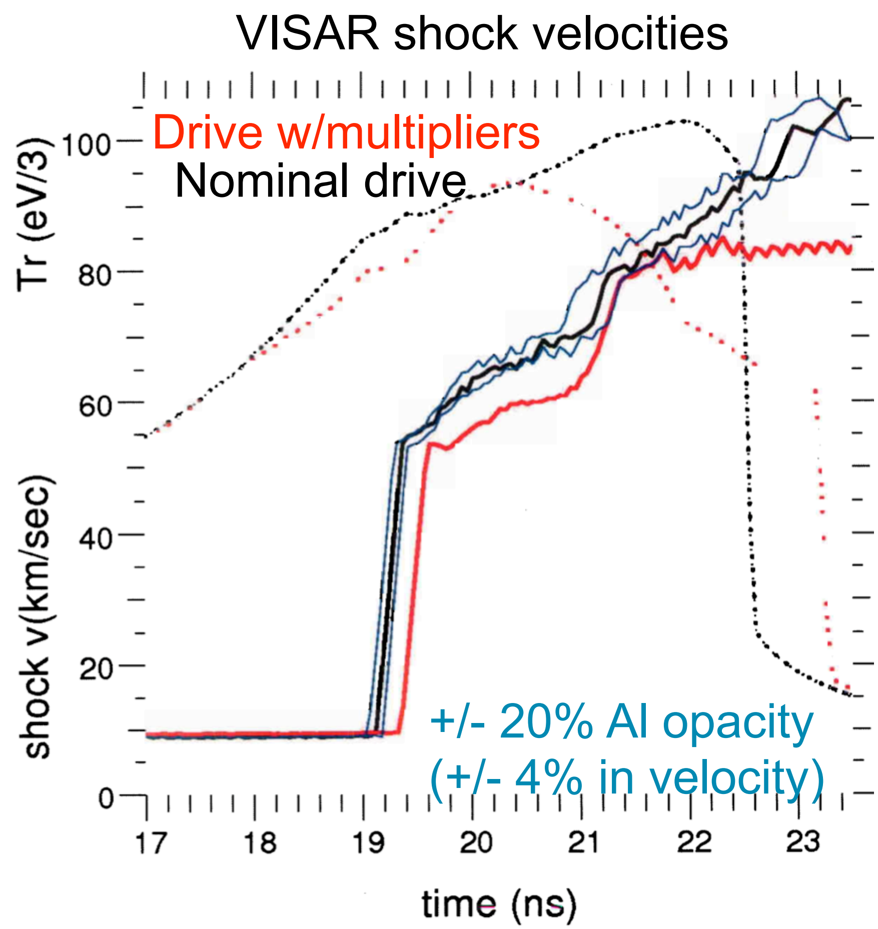
Solid Al sphere "olive"

Au cone/hohlraum identical to keyhole target (at 35K)



Shock speed is insensitive to experimental uncertainties relative to the drive multipliers needed to match implosion data

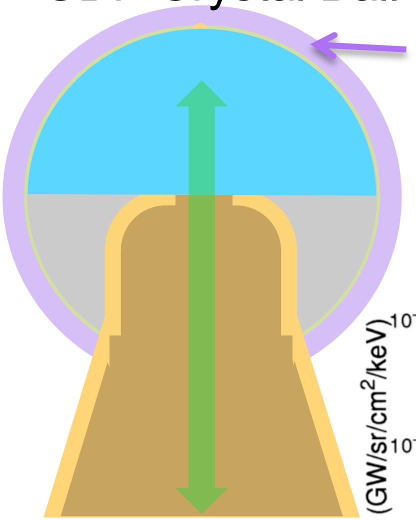




Visar speed error +/-1 %

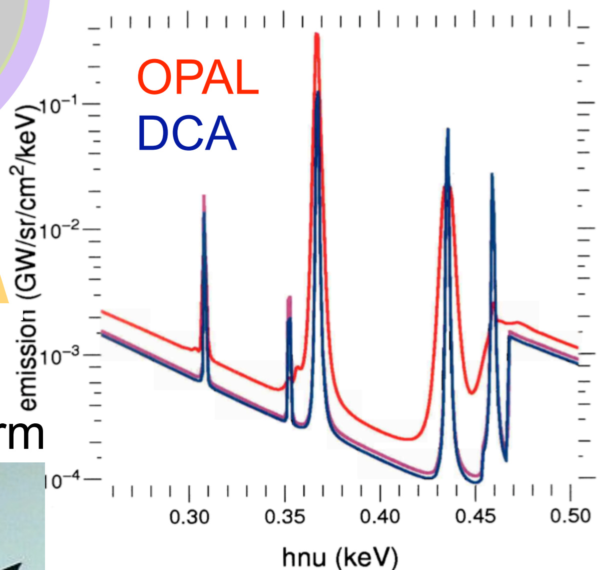
Assuming the first experiments constrain the x-ray drive, we can use the Crystal Ball to examine GDP ablation physics

GDP Crystal Ball

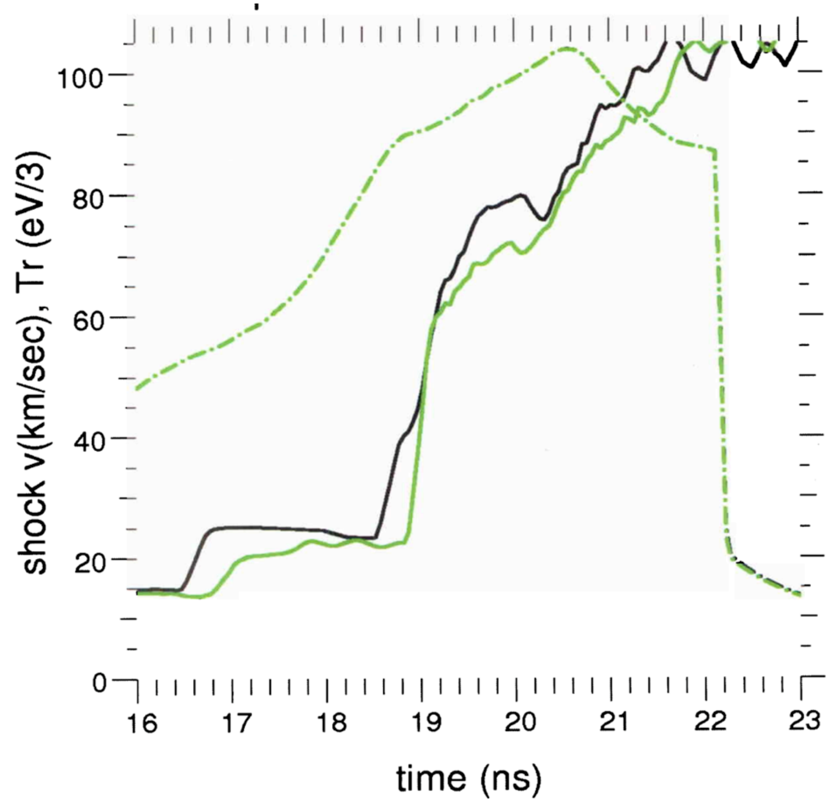


180 μm GDP layer

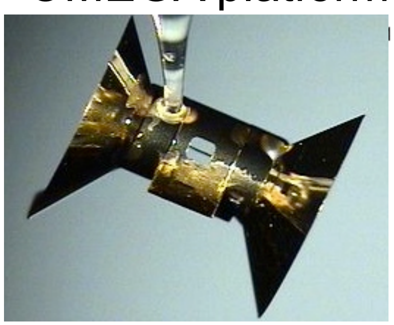
Carbon emission



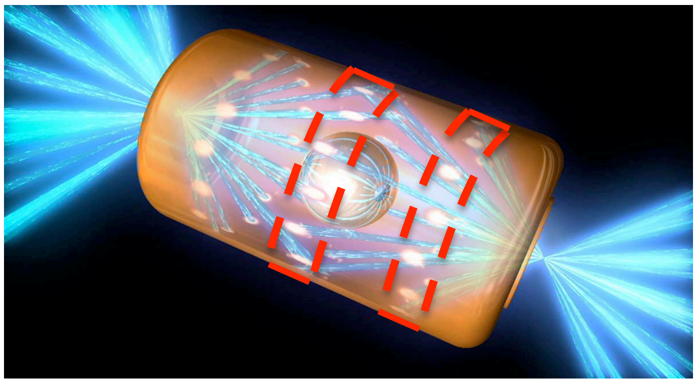
DCA opacity model shows a delayed, reduced velocity history vs OPAL



OMEGA platform

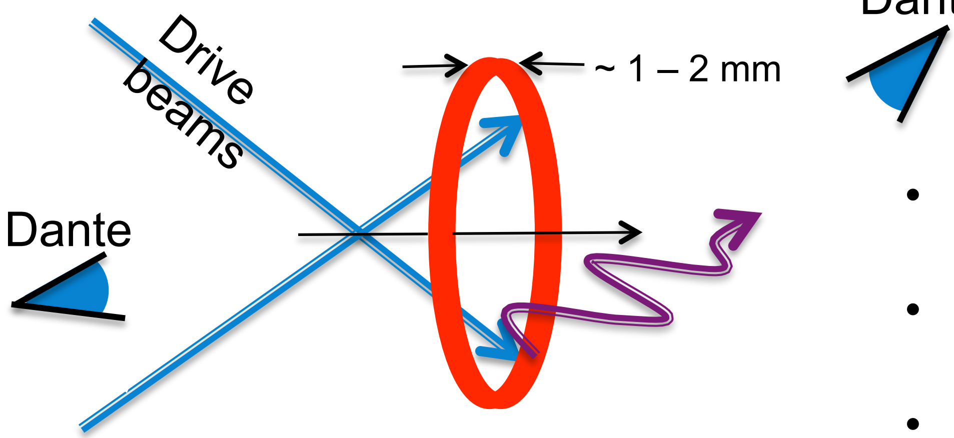


Other experiments being considered:
Wedding M-band Experiment diagnoses Au M-band without multiple absorption/re-emission events



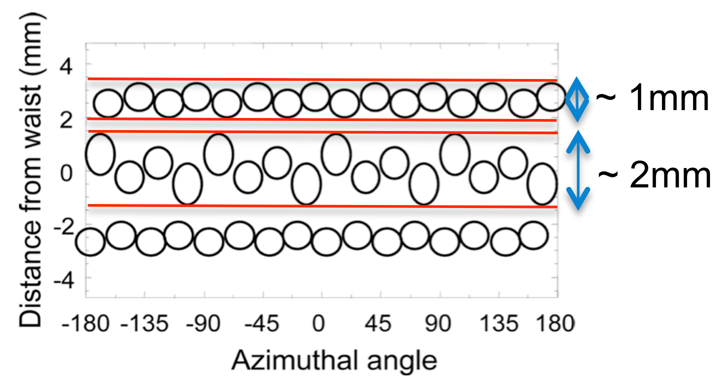
Au Ring for inner and outer cone NIF beams:

Dante



Thomson scattering diag. if available

- Ring diameter matches that of present NIF hohlraum
- Width of rings just enough to fully subtend laser spots

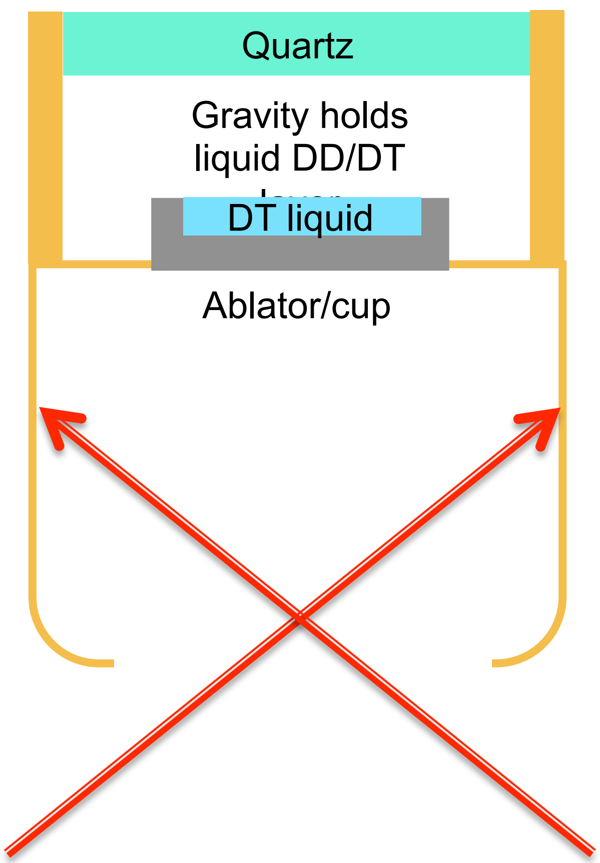


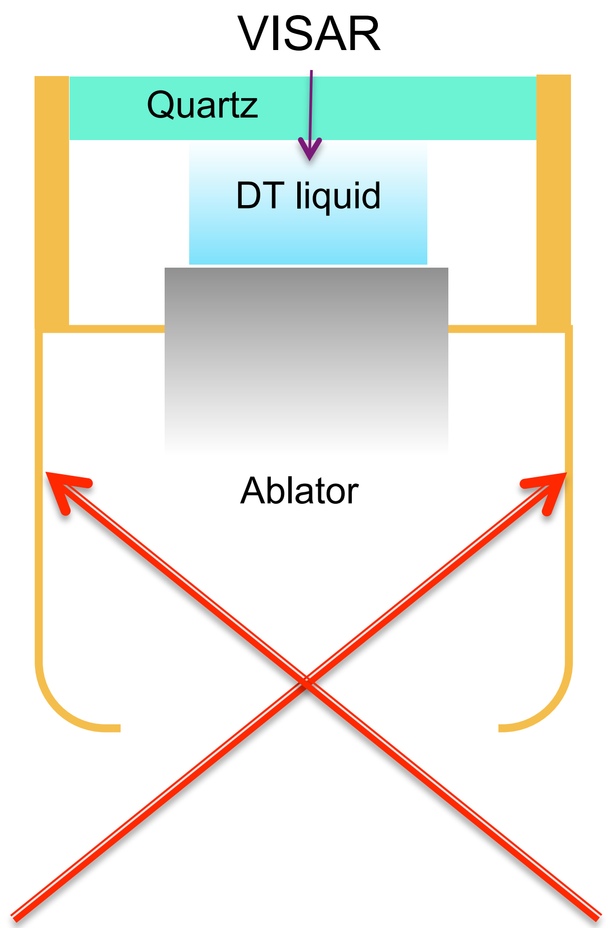
- 1 Ring for each cone set (shot separately)
- 1 Ring for pure Au and one for Au coated U hohlraum materials
- Two Dante lines of sight
- ~6-8 NIF experiments

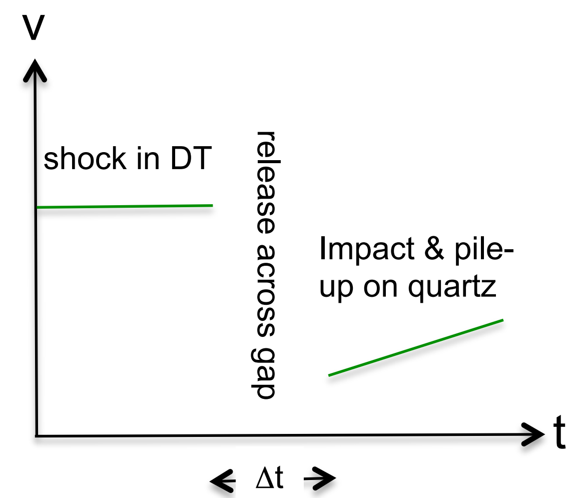
Other experiments being considered:

DT shock-release experiments - liquid DT is shocked then released across gap to impact quartz

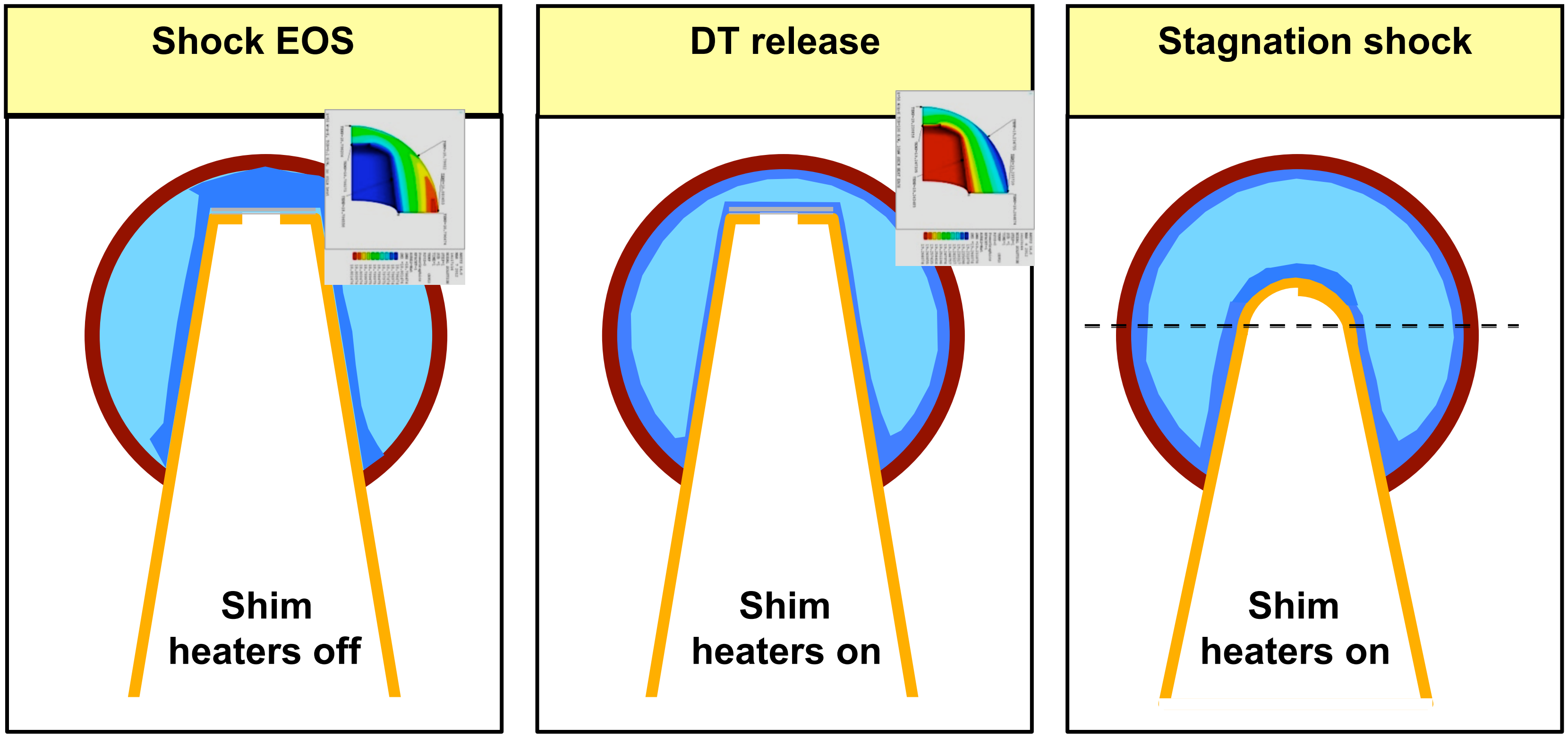
Release of DT effects hot spot adiabat, stagnation pressure





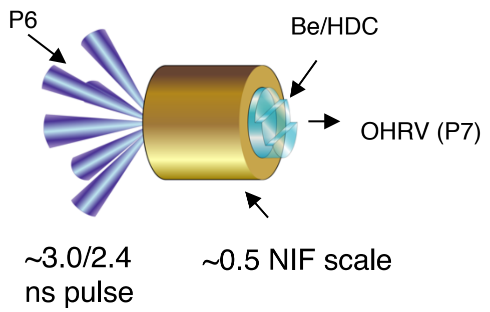


Other experiments being considered:
DT shock and release experiments in keyhole geometry



Other experiments being considered:
Capseed-B4C: Shock imprinting test of near term alternate ablator option

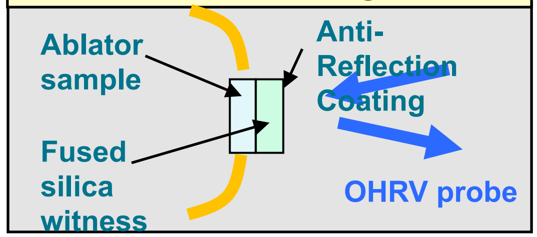
Omega Capseed Experiment for OHRV platform



- **Hohlraum size scaled from NIF to match Omega power**
- **Laser intensity & fraction of wall illuminated same as NIF**

Up to 12 Omega targets
- B4C/B4C+2%Si shots:
  - Energies: up to 280 J/beam
  - Captures foot of NIC pulse

Planar Package

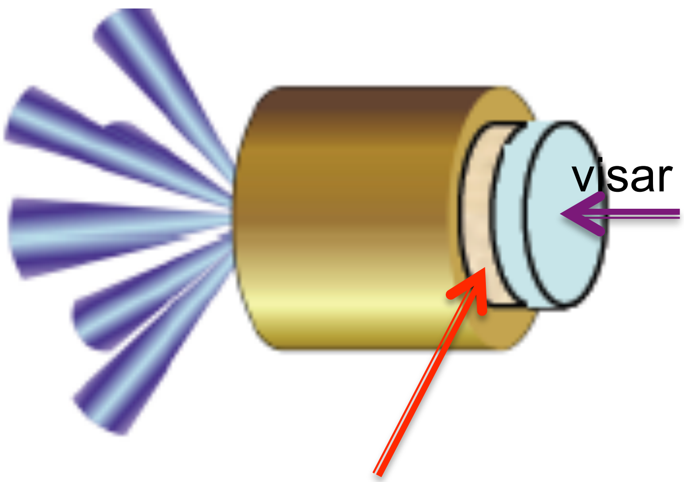


- 2.7 mm diameter x 2.0 mm long halfraum
- Package B4C & B4C-2%Si & 500-750 μm fused silica window with AR coating to suppress external probe beam reflection

Add Al, Si, etc.

Other experiments being considered:
Planar ablator dynamics experiment using full NIC-like drive could quickly sort thought alternate ablators

NIF Halfraum (gas filled) with NIC-like drive (through 4th shock)



Planar ablator sample – planar samples are quickly produced by target fab. as compared to capsules

Alternate Ablators Ranking by Pressure Generation

Material	Z_{max} (<8)	ρ (g/cc)	P~ρ(Z+1)/A	$c\sim[(Z+1)/A]^{1/2}$
Diamond	6	3.51	2.05	0.76
Boron Carbide	6	2.52	1.41	0.75
Boron	5	2.46	1.37	0.75
Graphite	6	2.25	1.31	0.76
Boron Nitride	7	2.25	1.27	0.75
Graphite Epoxy	6	1.84	1.14	0.79
Beryllium	4	1.86	1.03	0.74
Paralene	6	1.28	0.884	0.83
Polystyrene	6	1.046	0.723	0.83

Shoot Al ablator 1st as a drive standard

While this configuration won't match what a real capsule would see exactly, it would reveal which ablators behave as modeled and which don't, helping pinpoint atomic physics, radiation transfer, or modeling issues of certain materials

Understanding of ablation and capsule drive should improve through modeling and the design of experiments to help unravel the relevant physics

- EOS and Opacity deviations from nominal models, including NLTE effects might explain some of differences with data
- Double ablation front in DCA models, if real, would be undesirable feature affecting symmetry, stability, shock history
- Experiments targeting hypotheses for degradations of capsule performance as well as to enable alternate concepts are planned or under consideration
- Experiments are scheduled to help sort out relative contributions of x-ray drive and ablator response: the Crystal ball (June 2012) and Viewfactor (July 2012)